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A MOBILE DRINKING WATER TREATMENT RESEARCH FACILITY FOR INORGANIC CONTAMINANTS REMOVAL

Design, Construction, and Operation

by

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Cooperative Agreement CR806073

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16. ABSTRACT

This report describes the field research capabilities of the 10-ft wide by 40-ft long transportable research facility and summarizes its design, construction, and operation. With an October 1981 replacement value of $182,000, the mobile facility contains a complete analytical laboratory and an 8 L/min pilot plant with interconnected RO, IX, AA1, and EDR units. The treatment technologies applicable to a given contaminant removal problem are operated separately over a period of several months. The resulting performance data for all processes are then compared on technical and economic bases and appropriate general recommendations are made for that type of contaminant removal problem.

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FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution, and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research and is a most vital communication link between the researcher and the user community.

This report describes the design, construction, and operation of a mobile, reusable drinking water treatment research facility. It is now being used in various small communities to develop treatment techniques for the removal of inorganic contaminants, particularly nitrate, fluoride, arsenic, selenium, chromium, radium, and barium.

ABSTRACT

It has been estimated that there are several thousand public water supplies in small communities in the U.S. which contain fluoride, nitrate, arsenic, selenium, radium, barium, or chromium in concentrations in excess of the maximum contaminant limits (MCLs) established in the National Interim Primary Drinking Water Regulations. Previous experience and research had indicated that these primarily ionic contaminants could be removed by advanced water treatment processes such as packed beds of activated alumina (AA1) or ion-exchange (IX) resins or by reverse osmosis (RO) or electrodialysis (EDR) separation. However, reliable design criteria and economical operating procedures were not available for the selection, cost-effective application and safe operation of these little-understood processes. This was especially true for small community water supply treatment where single contaminant removal was desired in waters containing more than 1000 mg/L of total dissolved solids.

To provide help for small communities, a long-term EPA-funded project has been undertaken to evaluate the single contaminant removal processes (AA1 and IX) vs the desalting processes (EDR and RO). This is being done by operating a mobile drinking water treatment research facility on contaminated water sources in a series of small U.S. communities. Initial field evaluations are being done in the southwestern U.S. on fluoride, nitrate, or arsenic contaminated groundwaters. The first two community water supplies evaluated for selection of treatment technologies were Taylor, Texas (3.0 mg/L F^-) and Glendale, Arizona (19.0 mg/L NO_3-N).

This report describes the field research capabilities of the 10-ft by 40-ft transportable research facility and summarizes its design, construction, and operation. With an October 1981 replacement value of $182,000, the mobile facility contains a complete analytical laboratory and an 8 L/min pilot plant with interconnected RO, IX, AA1, and EDR units. The treatment technologies applicable to a given contaminant removal problem are operated separately over a period of several months. The resulting performance data for all processs are then compared on technical and economic bases and appropriate general recommendations are made for that type of contaminant removal problem. Finally, complete technical reports are prepared for each research location.

This report was submitted in fulfillment of Cooperative Agreement No. CR 806073 by the University of Houston under the sponsorhip of the U.S. Environmental Protection Agency. This report covers the period July, 1978 to August, 1981, and work was completed as of December, 1981.

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ABBREVIATIONS AND SYMBOLS

AA	Atomic absorption spectroscopy, an analytical method
AA-1	Activated alumina column No. 1
AA1	Activated alumina adsorption process
A	Ampere, coulomb sec
AG-1	Agitator No. 1
AG	Aluminum-containing filter media
Alk	Alkalinity, mg/L as $CaCO_3$
BIZ	An enzyme detergent
BV	Bed volume, volume of media including voids
C	Concentraton, mg/L
$CaCO_3$	Concentration expressed as mg/L of $CaCO_3$
C_F	Concentration in feed, mg/L
CG-1	Calibration gauge No. 1
C_I	Concentration at column inlet, mg/L
C_P	Concentration in product water, mg/L
CV-1	Check valve No. 1
E	Suffix designating that a component is inside the EDR unit
EDR	Electrodialysis with reversal
EDTA	Ethylenediaminetetra acetate, a chelating agent
EPA	U.S. Environmental Protection Agency
F-1	Filter No. 1
GAC	Granular activated carbon
Gel	A microporous ion exchange resin
HMP	Sodium hexametaphosphate, a polyphosphate antiscalant
IX	Ion exchange process
IX-1	Ion exchange column No. 1
IC	Ion chromatography, an analytical method
JTU	Jackson turbidity unit, also FTU, NTU
NC	Normally closed valve port
NO	Normally open valve port
MGD	Millions of gallons per day
MCL	Maximum contaminant limit, mg/L
NO_3-N	Nitrate concentration reported as nitrogen, mg/L
P-1	Pump No. 1
PG-1	Pressure gauge No. 1
PR-1E	Pressure regulator No. 1 in EDR unit
PS-1	Pressure switch No. 1
Quat.	Quaternary amine, strong-base anion resin

R-1	Rotameter No. 1
RO	Reverse osmosis process
RO-1	RO module No. 1
RV-1	Relief valve No. 1
SBA	Strong-base anion exchange resin
SDI	Silt density index, dimensionless
SDWA	Safe Drinking Water Act
SV-1	Solenoid valve No. 1
T-1E	Sample tap No. 1 in EDR unit
T-1	Tank No. 1
TDS	Total dissolved solids, mg/L
TH	Total hardness as $CaCO_3$, mg/L
V-1	Manual valve No. 1
WBA	Weak-base anion exchange resin
$\alpha_{N/Cl}$	Nitrate/chloride separation factor, dimensionless
µmho	Micromho-cm specific conductance; also S, microSiemens

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DRINKING WATER TREATMENT RESEARCH FACILITY

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SECTION 1

INTRODUCTION

INORGANIC CONTAMINANT REMOVAL PROCESSES

Four of the inorganic contaminants listed in the EPA National Interim Primary Drinking Water Regulations [1] are anions or generally occur as anions in those waters where they are found; these are fluoride, nitrate, arsenic, and selenium. Table 1 lists the maximum contaminant limits (MCL's) for these substances.

Two distinct types of processes may be considered for removal of these ions: single contaminant removal processes (e.g., alumina adsorption and ion exchange), and desalting processes (e.g., electrodialysis and reverse osmosis). Single contaminant removal will generally cost less than desalting but desalting will yield a softer, more palatable and less corrosive water for distribution. Each contaminant removal application will be different because the background raw waters are different in TDS level and chemical composition. Thus it is desirable to have available desalting processes and single contaminant removal processes when doing contaminant removal research. How each of these processes is used to remove the contaminants is explained in an article by Clifford [5] entitled "Processes for the Removal of Inorganic Contaminants."

TABLE 1. POTENTIAL ANIONIC CONTAMINANTS FOR WATER SUPPLIES

Contaminant	MCL, mg/l	Common Form in Ground Water (pH=6-9)
Fluoride	1.6	F^-
Nitrate (as N)	10.0	NO_3^-
Arsenic	0.05	$H_2AsO_4^-$, $HAsO_4^=$, $HAsO_2$, AsO_2^-
Selenium	0.01	$SeO_4^=$, $SeO_3^=$, $HSeO_3^-$

*Annual average of maximum daily air temperature = 70.7 - 79.2°F.

SINGLE CONTAMINANT REMOVAL PROCESSES

The literature indicates that fluoride, arsenite, arsenate, selenate, and selenite can be removed from low or high TDS water supplies by precipitation or coprecipitation with lime, alum, or iron salts. Unfortunately, precipitation processes are not readily adaptable to small water systems or individual wells that must operate on demand. The negative features of coagulation-precipitation processes in these applications include the necessity for sludge collection, dewatering, disposal, and long start-up and shut-down periods.

Fluoride and arsenic have been removed from water supplies using packed beds of bone char or tricalcium phosphate. However, these media tended to degrade by attrition and continuously lose capacity after successive regenerations. Packed beds of activated alumina and anion exchange resins have been chosen for this single contaminant removal research. Such columns can be operated on demand and are generally free from the above-mentioned disadvantages of both precipitation processes and packed-bed processes using bone char and tricalcium phosphate.

DESALTING PROCESSES

For desalting small flows of brackish water, electrodialysis (ED) and reverse osmosis (RO) are the methods of choice. Electrodialysis removes ions from water; RO removes water from ions. In both processes, low molecular weight (< 200), uncharged species tend to pass through into the product water. However, properly operated RO units will completely remove bacteria, viruses and silica, whereas ED units will not. Finally, the desalting processes may be expected to do a fair-to-good job of removing the inorganic contaminants of interest even in high (> 1000 ppm) TDS waters. Table 2 compares the single contaminant removal and desalting processes for the removal of fluoride, nitrate, and the various forms of arsenic and selenium. Entries in the table are primarily based on theory and bench-scale research findings except for fluoride removal, which has been practiced on a large scale (i.e., municipal defluoridation plants).

A REUSABLE, TRANSPORTABLE RESEARCH FACILITY

In the planning stages of this project, it was realized that it would be necessary to build pilot-scale water treatment facilities for some contaminant removal applications where insufficient process design information was available. When the pilot studies were finished, an in-place pilot plant would be nearly worthless. That would not be the case if the pilot plant was transportable and adaptable to many situations.

In 1977, the need was realized for a reusable drinking water treatment research facility of universal design to study the removal of the widespread inorganic contaminants listed in Table 1. Groundwater supplies contaminated with one or more of these anions had been found in all 50 states, particularly in small communities in the southwest.

TABLE 2. POTENTIAL* FOR CONTAMINANT REMOVAL BY VARIOUS PROCESSES

CONTAMINANT	PACKED BEDS		REVERSE OSMOSIS	ELECTRODIALYSIS
	Activated Alumina pH 5.5 - 7.5	Strong Base Resins pH 5-9	Cellulose Acetate or Aromatic Polyamides pH 6 - 8	pH 6 - 8
Fluoride	G	P	G	G
Nitrate	P	F	F/G	F/G
Arsenic (III)	F/P	P[1]	P/F	P/F
Arsenic (V)	G	P/G[2]	G	G
Selenium (IV)	G	F[3]	G	G
Selenium (VI)	F	G[4]	G	G
Chromium (VI)	F	G	G	G

G = Good F = Fair P = Poor: These are relative rankings for the process in question

Notes: For Electrodialysis and Reverse Osmosis at 50 - 80% Recovery
Good means greater than 80% removal in "typical" ground water
Fair means 40 - 80% removal
Poor means less than 40% removal

For Packed Bed Processes
Good means that the ion is highly preferred relative to Cl^-
Fair means that the ion is a preferred ion relative to Cl^-
Poor means that the ion is not a preferred ion relative to Cl^-

(*) Potentials are based on published experimental results except where noted
[1] H_3AsO_3, the uncharged species, predominates at pH's below 9.2
[2] Poor at pH's below 7 ($H_2AsO_4^-$), good at pH's above 7 ($HAsO_4^=$)
[3] Estimated, based on the elution of selenite in ion chromatography
[4] Estimated, based on the elution of selenate in ion chromatography

The concept of a reusable pilot plant was thought to be particularly applicable to these diverse small communities with few sources of technical assistance and little ability to pay for engineering or construction. In July 1978, an EPA-funded research project was started at the University of Houston to design, construct, and operate a transportable, reusable, pilot-plant facility for inorganic contaminant removal.

RESEARCH OBJECTIVES

The Mobile Drinking Water Treatment Research Facility, backed up by bench scale research at the University of Houston, was designed to achieve the following objectives:

(1) To evaluate RO (Reverse Osmosis), IX (Ion Exchange), AA1 (Activated Alumina) adsorption, and EDR (Electrodialysis with Reversal) for the treatment of small community water supplies for the removal of the SDWA (Safe Drinking Water Act, PL 93-523) contaminants, especially fluoride, nitrate, selenium, and arsenic.

(2) To obtain valid design and cost information for the scale-up of these processes.

(3) To develop recommended means for the most economical operation of each of these processes, i.e., to establish:

- pretreatment requirements for all processes
- bypass water allowances for all processes
- operating pressure and yields for the desalting processes
- types of resins and membranes
- minimum bed depths and detention times
- chromatographic behavior of ions being eluted from packed beds
- regenerant concentration and flow direction

(4) To compare RO, IX, AA1 adsorption, and EDR on the following technical and economic bases:

- removal efficiencies for all the SDWA contaminants
- applicability to waters of varying ionic composition and TDS level
- overall water quality of the treated water as measured by TDS, hardness, organic content, taste, and odor

-- effects of Ca, Mg, Fe, Mn, organics, and SiO_2 fouling

-- wastewater disposal requirements

-- complexity of operation for small community water supplies

-- degree of operator skill required

-- degree of automation feasible and necessary

-- minimum chemical and physical monitoring requirements

-- labor and materials for operation and maintenance

-- chemical storage and handling requirements

-- public health risk in event of process failure

-- installed capital costs, $/daily gallon of product water

-- total operating costs, $/volume of product water

CONSTRUCTION AND INITIAL OPERATION

Actual construction began in February 1979 and was completed in March 1980. The completed pilot plant was transported to Taylor, Texas (population 13,000) in early April 1980, where it remained until March of 1981. Debugging and pilot-scale testing were accomplished in Taylor, where fluoride removal was studied in a 3.0 ppm F^-, 1100 ppm TDS groundwater using activated alumina adsorption, electrodialysis, and reverse osmosis.

On March 16, 1981 the mobile research facility was moved to Glendale, Arizona (population 90,000), a suburb of Phoenix, where 10 out of 32 water wells have been shut down because of high nitrates. There, ion exchange, electrodialysis, and reverse osmosis are being studied for nitrate removal from a 19.0 ppm NO_3-N, 500 ppm TDS well water.

Although the mobile facility spent 11 to 14 months at each of its first two locations because of the need for debugging and training of a new field researcher, subsequent stops will be shorter, typically 3 to 8 months in duration.

Experience from the first two moves has shown that the facility is readily transportable and reusable. The pilot-scale treatment systems have operated very well, and much valuable pilot-scale data have been obtained. This report is not a detailed or comprehensive account of the work done in Taylor or Glendale. Rather, it is meant to be a comprehensive report on the concept, design, construction, and operation of the mobile research facility. A separate report will be issued for each field location (e.g., "Fluoride Removal Studies in Taylor, Texas" and "Nitrate Removal Studies in Glendale, Arizona").

SECTION 2

MOBILE RESEARCH CONCEPT

PROJECT OVERVIEW

The mobile, water treatment pilot-plant system (Figure 1) comprises a 10'x40' research trailer, (Figure 2) a pick-up truck containing a 300-gallon wastewater tank and a 31 ft travel trailer (Figure 4). The large research trailer (Fig. 3) is transported between sites by a professional tractor-trailer driver while the travel trailer is pulled by the pick-up truck (Figure 4) driven by the field researcher.

While on location in the field, connections are made to the research trailer to supply raw water (avg. 8 L/min), electrical power (100A, 220V), and telephone service. Unused treated waters and non-toxic wastewaters are disposed of through discharge lines to a nearby sewer or by surface spreading (grass watering). Toxic wastewaters, e.g., concentrated As or Se solutions, are pumped into the 300-gallon tank in the pick-up truck, and transported to an ultimate disposal site.

During the 3-12 month period at a given field location, the field researcher (and possibly his or her mate) lives in the travel trailer. This is generally located in a nearby trailer park where complete utility hookups are available.

PROJECT STAFFING FOR FIELD WORK

Both water treatment process research and water analyses are done in the large research trailer which is divided into two sections (Figure 1). The rear 2/3 of the space is devoted to the pilot plant while the forward 1/3 contains the analytical laboratory and office. Ideally, the field researcher is an environmental or chemical engineer with analytical chemistry skills. He or she does both the pilot-plant experiments and the water analyses or supervises the water analyses. Other personnel involved in the research include the principal investigator (PI), environmental engineering graduate students, part-time analytical chemist, and outside contractors. The PI supervises the design and execution of all experiments by phone, letter, and site visits. Graduate students are occasionally sent to the field locations to assist the field researcher for periods of two to six weeks. Part-time chemists who are local residents are used to assist in the analytical work whenever possible. Finally, outside contractors are hired to move the trailer, install the electrical power, and maintain the instruments and con-

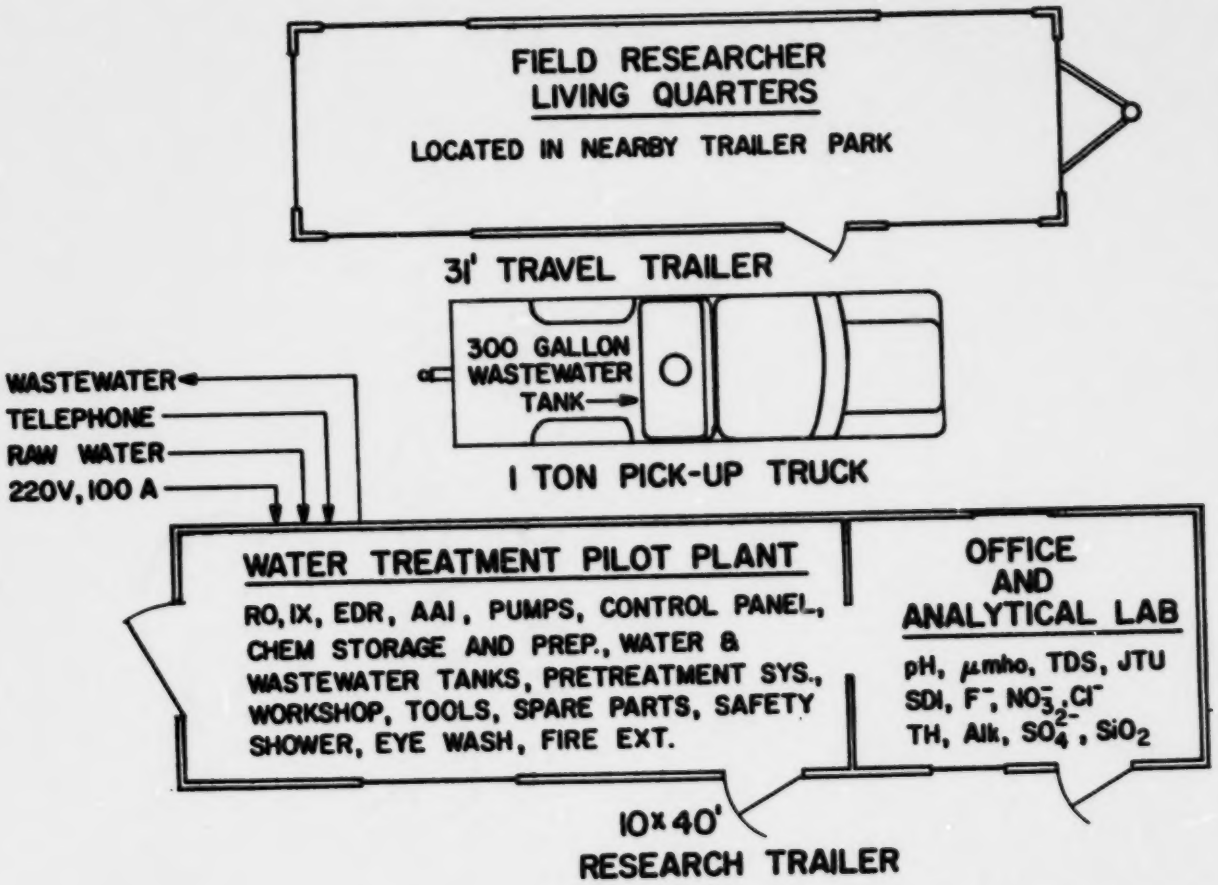


Figure 1. Mobile research concept including transportable pilot plant/ laboratory, travel trailer, and pickup truck.

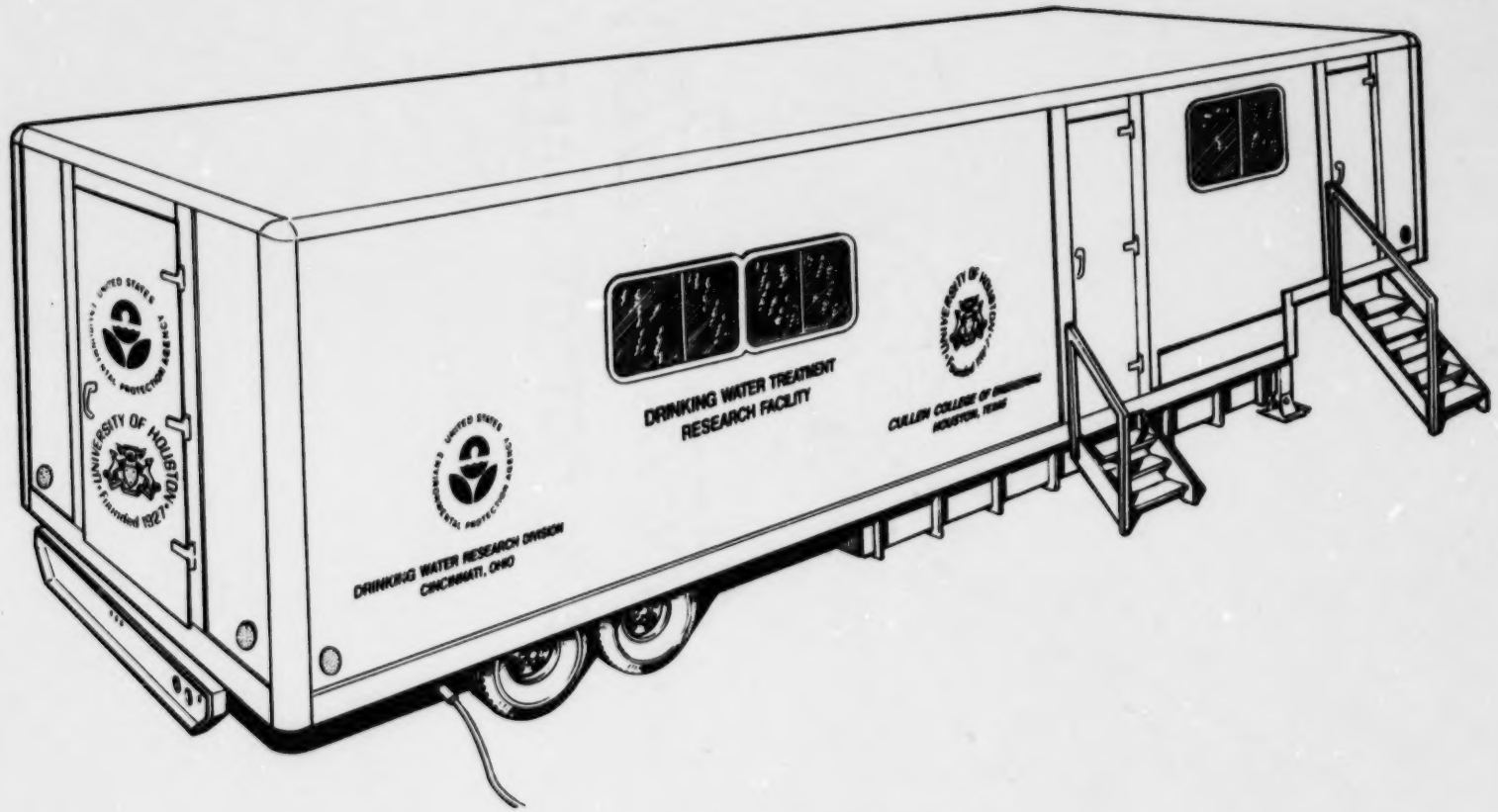


Figure 2. Exterior perspective drawing of mobile research facility.

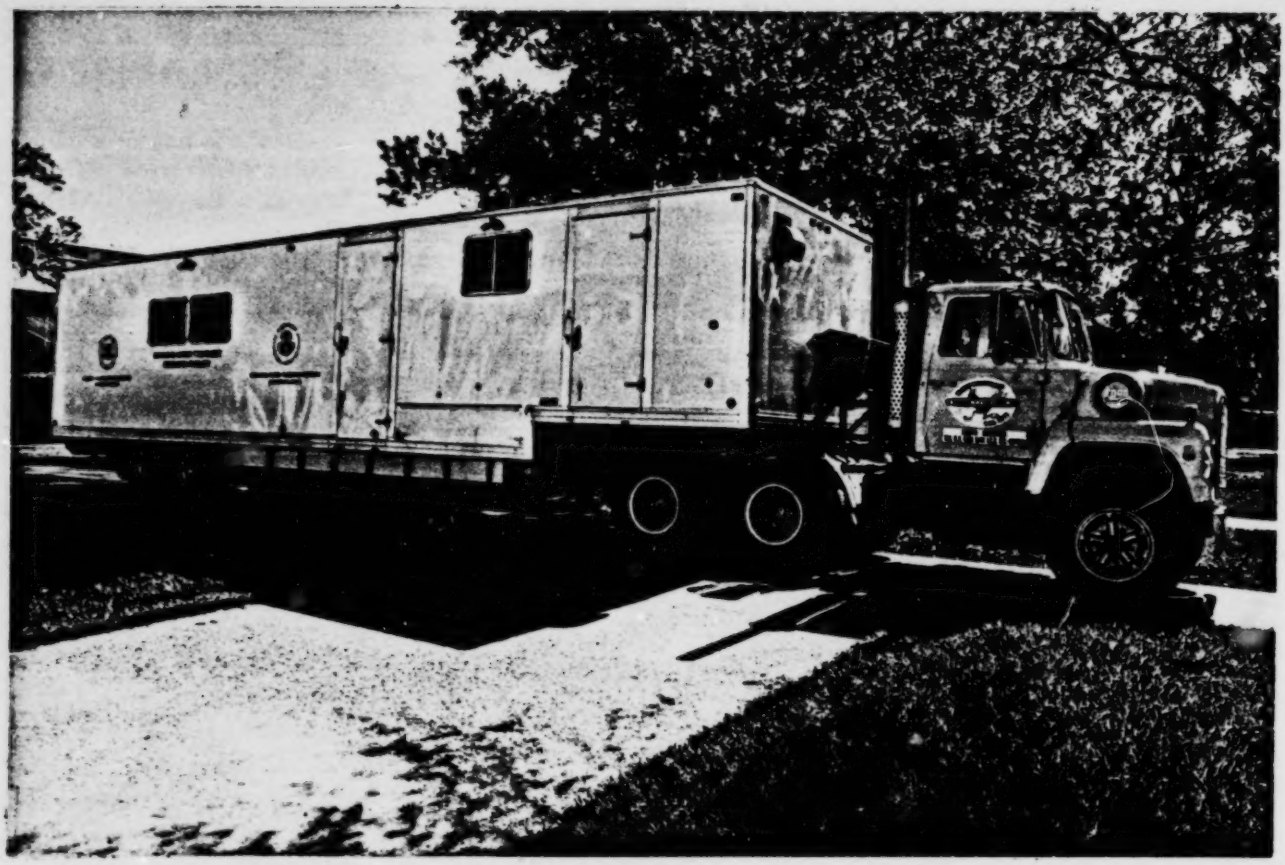


Figure 3. UH/EPA Mobile Drinking Water Treatment Research Facility shown hooked up to contract hauler's tractor leaving the University of Houston on its way to Taylor, Texas.

Figure 4. Pick-up truck and travel-trailer living quarters for operator of mobile drinking water treatment research facility.

trol systems.

SELECTING FIELD LOCATIONS

Small community water supplies to be evaluated for contaminant removal studies are selected by the principal investigator on the basis of:

(1) severity of fluoride, arsenic, nitrate, selenium, or radium contaminant levels and demonstrated health effects

(2) degree of cooperation expected from the community as determined by prior communications and a site visit by the PI

(3) levels of TDS and competing ions, especially sulfate. High TDS (1000 ppm) supplies are of particular interest for comparing the desalting technologies (EDR and RO) to the single contaminant removal processes (activated alumina adsorption and ion exchange). Sulfate is of special interest because it competes favorably with the contaminants for adsorption sites on alumina and anion exchange resins.

(4) presence of foulants such as Fe, Mn, silica, and organics. Attempts will be made to choose supplies such that each of these might eventually be studied.

(5) EPA (Drinking Water Research Division), state, and local government agreement that the supply to be studied will produce useful and timely results

MOVING TO NEW LOCATIONS

Generally, a period of three weeks is required to complete operations at one site, pack, move to a new site, unpack and start up the research facility at the new location. The principal investigator makes any necessary preliminary arrangements at each new site during his visit. The availability and analysis of contaminated water must be verified and the exact trailer location specified. He does this with the cooperation of the city manager, mayor, city council, and public works personnel. Necessary utilities must be available nearby and the contaminated well must be pumping either continuously, or intermittently with adequate water storage capacity.

At each new location the field researcher locates a trailer park to live in, establishes a post office box and bank account, and rents any necessary storage space. He sees to it that raw water, electrical power, phone and drains are hooked up to the research facility. He unpacks the laboratory equipment and prepares the pilot-plant for operation. A complete water analysis is done at the mobile lab before the pilot-scale experiments begin.

SECTION 3

FEATURES AND SPECIFICATIONS AND EXAMPLE OPERATING RESULTS

GENERAL SPECIFICATIONS

The research trailer is 10 feet rather than the usual 8 feet wide. This is to provide a safe and comfortable working environment for the field researchers. Twelve-foot wide mobile offices and homes were available as the basic unit but were rejected as being too wide and too flimsy for rugged use and repeated moving. The basic trailer shell was constructed of aluminum according to UH specifications by General Truck Body Inc. of Houston, Texas on a twin I-beam, an 8-wheel chassis. The detailed shell and chassis specifications are listed in Table 3.

Although the 10-foot wide trailer is considered a wide load, permits to move it are readily obtained by the contract haulers. According to the drivers who have moved the research trailer, the extra width presented no real problem. By tractor-trailer standards, it is considered a light load and was pulled as easily as a standard 8-foot wide trailer. It is estimated that the unit will spend at least 98 percent of its life in fixed-locations and only 2 percent in transport. Therefore, the slight disadvantage in transporting the wide load is more than compensated for by the extra space and comfort realized while it is stationary.

The pilot plant and the laboratory sections have separate entrance doors and each entrance is provided with a removable stairway with an attached safety railing. Additionally, the pilot plant section has an extra wide (46 in, 1.17 m) equipment door which doubles as an emergency exit. A sliding door inside the trailer allows the pilot plant to be isolated from the analytical laboratory. Six flood lights are mounted high up on the outside of the trailer. These automatically turn on at night to illuminate the entrances and generally the area around the trailer to help minimize vandalism. One double window in the pilot plant and two single windows in the laboratory provide ventilation, natural lighting, and a pleasant view of the surrounding area.

A special effort was made to rigidly fasten all of the pilot plant and laboratory equipment to either the floor or walls for protection during transit. Unistrut channels have been used throughout the trailer on the walls and ceiling for mounting the flow system piping and components, and the PVC electrical conduit and control boxes. Also, weatherproof electrical outlets,

TABLE 3: CHASSIS AND SHELL SPECIFICTIONS FOR UH/EPA RESEARCH TRAILER

Length: 40 ft (12.2 m)

Inside height: 90 inches (2.29 m)

Outside width: 10 ft (3.05 m)

I-beam chassis with steel understructure

Z-bar aluminum uprights on trailer shell

White aluminum-sheet, exterior walls

Double axle, 8 wheels for 20,000 lb (9,080 kg) Gross Vehicle Weight

1200 x 16.5 x 10 tires

All necessary brake and running lights

Air brakes and kingpin for connection to standard tractor

Two 31-inch (0.79 m) wide entrance doors with stairs and safety railings

46-inch (1.17 m) wide service door for equipment loading

Four screened plexiglass windows (2'x3' each) (0.61 x 0.91 m each)

5 ft x 10 ft x 18 in (1.52 x 3.05 x 0.457 m) underbody storage compartment with 2 hinged doors

2 in (5 cm) thick block polystyrene foam insulation in walls and ceiling

1/2 in (1.27 cm) thick plywood interior walls mounted on 1 in x 4 in (2.54 x 10.2 cm) hardwood strips

1/4 in (0.64 cm) thick plywood on ceiling mounted on 1 in x 4 in (2.54 x 10.2 cm) hardwood strips

Butyl-rubber caulking for interior wall joints

Silicone-rubber caulking in floor/wall joints

Epoxy-resin floor coating and epoxy painted walls

36,000 BTU/hr air conditioner; 45,000 BTU/hr electric heater

wall-switches and control enclosures have been used throughout the pilot plant and lab for protection against possible process spills.

Corrosion resistant plastics (PVC, plexiglas, teflon, polyethylene, and nylon) were used wherever possible for the pumps, valves, columns, and piping. Such a widespread use of plastics would not have been possible if organic rather than inorganic contaminants were being studied. Stainless steel, nylon, and fiberglass reinforced plastics were used in the reverse osmosis system where pressures in excess of 400 psig (2760 kPa) were expected. Finally, wherever possible, the pilot plant components were duplicated in the system design so as to provide readily available replacements in the event of failure.

PILOT-PLANT LAYOUT AND EQUIPMENT

The treatment processes are laid out in a left to right flow scheme on one wall of the pilot plant, as can be seen in the interior layout, Figures 5 and 6. The feedwater, acid and base tanks, and pumps are located on the left side of the four processes and the 200 L (55 gal) polyethylene, treated-water and wastewater collection tanks and pumps are on the right. Larger 1100 L (300 gal) fiberglass, water and wastewater storage tanks are mounted underneath on either side of the trailer. Each of the treatment processes is controlled from the graphic control panel mounted on the process wall above the RO unit. Facing the control panel, the operator stands within easy reach of both the process equipment and the graphic controls. This arrangement was considered an important safety and convenience feature for the complex one-man research operation.

Work and storage areas occupy the wall across from the processes. The work benches are used for equipment repair, chemical preparation, and storage. Two 7 ft. high x 47 in. wide (2.13 x 1.19 m) storage cabinets are provided for spare parts, resins, alumina, and chemicals while the hand tools are kept in a rolling tool chest. A safety shower and eyewash fountain are located in the chemical preparation area near the utility sink.

On the wall between the pilot plant and laboratory immediately to the right of the pilot plant entrance are the four power breaker boxes; these are (1) main breaker, (2) air conditioner (3) electric heater, and (4) equipment and lighting breakers. The air conditioning heating unit is mounted on this same wall at the end of the process train while the A/C compressor is mounted on a frame on the outside of the front of the trailer.

LABORATORY LAYOUT AND EQUIPMENT

The analytical laboratory layout shown in Figures 5 and 7 features standard laboratory furniture with cast epoxy bench tops and color-coded drawer fronts. The laboratory also serves as the project's field office. As such, it contains a desk, file cabinet, book shelf, and telephone which is used for discussing experiments with the principal investigator, inputting data to the

University of Houston computing system, and making local calls regarding the day-to-day operations.

The laboratory is equipped so as to be able to analyze raw and treated waters for pH, dissolved solids, fluoride, chloride, nitrate, hardness, alkalinity, sulfate, and silica by the usual wet chemical methods [2, 3]. In addition, instrumentation has also been provided for the measurement of conductivity, turbidity, and silt density index (SDI); and pH, Cl^-, F^-, and NO_3^- ions using electrodes. An ion chromatograph will eventually be provided for the routine analysis of the common anions F^-, Cl^-, NO_3^-, and $SO_4^=$. Also a rugged atomic absorption spectrophotometer with a graphite furnace atomizer will be provided whenever the research trailer is being used to study arsenic or selenium removal.

Most of the water samples to be analyzed, especially product water and regenerants, are collected automatically by the ISCO sampler at times preselected by the field researcher. Other grab samples of the raw water and brine streams are collected when necessary. A detailed list of the important analytical laboratory equipment, including safety and office equipment, is provided in Table 4.

PILOT PLANT TREATMENT UNITS (Figures 5 and 6)

The primary components of the pilot plant are the four treatment units. Although they are interconnected, they were designed to be operated one-at-a-time rather than simultaneously. Each unit may be operated over a wide range of feed and product water flow rates. The average product water design flow was orignally chosen as 2 gallons/min (8 L/min) but practical considerations, e.g., the availabilities of reverse osmosis modules and electrodialysis stacks, dictated the actual product water design flow rates for the various units.

The 2 gal/min (8 L/min) activated alumina system is made up of two 8-inch (20.3 cm) diameter plexiglass columns containing 3 ft (0.91 m) of 28 x 48 mesh Alcoa F-1 activated alumina. The columns may be operated in series or parallel with upflow or downflow exhaustion and regeneration. The intended uses of the alumina system are fluoride, arsenic, and selenium removal and regeneration is accomplished using dilute (0.25 N) NaOH followed by acidification with dilute (0.50 N) H_2SO_4. Spent regenerants are either reused or combined, neutralized and disposed of locally.

The 2 gal/min (8 L/min) ion-exchange system is made up of two 10-in (25.4 cm) diameter plexiglass columns typically containing 3 ft (0.91 m) of anion or cation exchange resin. Single-bed or two-bed ion-exchange processes may be simulated with either upflow or downflow exhaustion and regeneration. Single-bed anion exchange with NaCl regeneration is the intended method for removal of nitrate, arsenic, and selenium. As with the alumina system, backwashing may be accomplished with raw water or with treated water from the storage tanks. In fact, with the exception of the column diameters, the alumina and ion-exchange systems are identicl and may be used interchangeably. Tanks and

TABLE 4: ANALYTICAL LABORATORY EQUIPMENT FOR UH/EPA RESEARCH TRAILER

Dionex Model 2010i single-channel ion chromatograph
Atomic Absorption Spectrophotometer with graphite furnace atomizer
Orion Model 901 microprocessor pH meter
Hach 2100 A turbidity meter
Hach Model 16300 portable conductivity meter
Hach Model 16400 expanded range portable pH meter
Drying oven
Mettler H-32 analyticl balance, shock mounted
Corning Mega-Pure 1-liter still, 1.4 L/hr of distilled H_2O to be demineralized
Cole-Palmer universal demineralizer cartridges, two in series
Electrodes: F^-, Cl^-, NO_3^-, Ag/AgS, pH, reference
Magnetic stirrers, hot plates, dessicator
Thermometer, stopwatches
Volumetric glassware: pipets, flasks, burets, etc.
Chemicals, buffers, miscellaneous lab equipment
Desk, file cabinet, bookcase
HP 41-C programmable calculator with printer
Eyewash stations, first aid kit, fire extinguisher

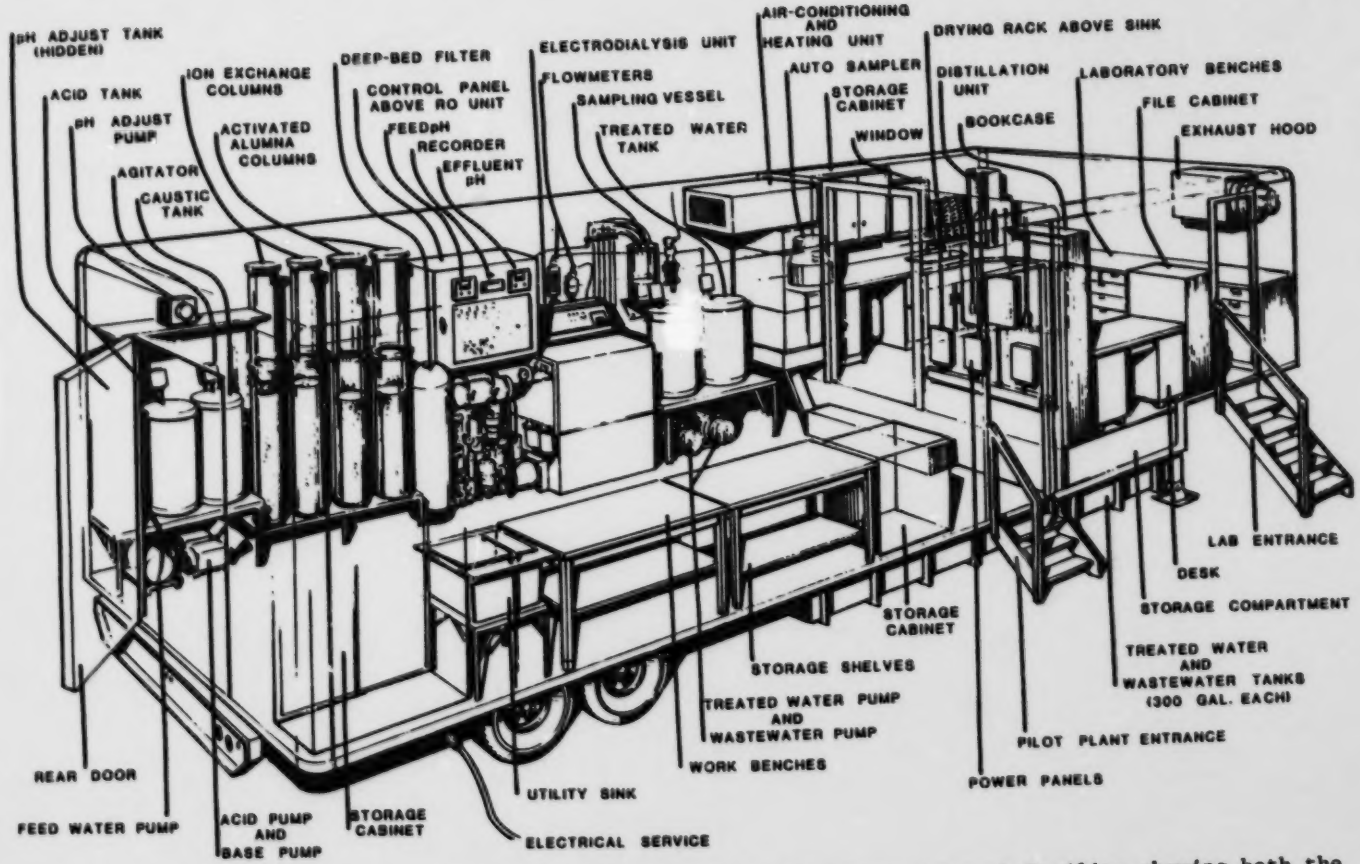


Figure 5. Interior layout of the UH/EPA Drinking Water Treatment Research Facility showing both the pilot plant and laboratory equipment.

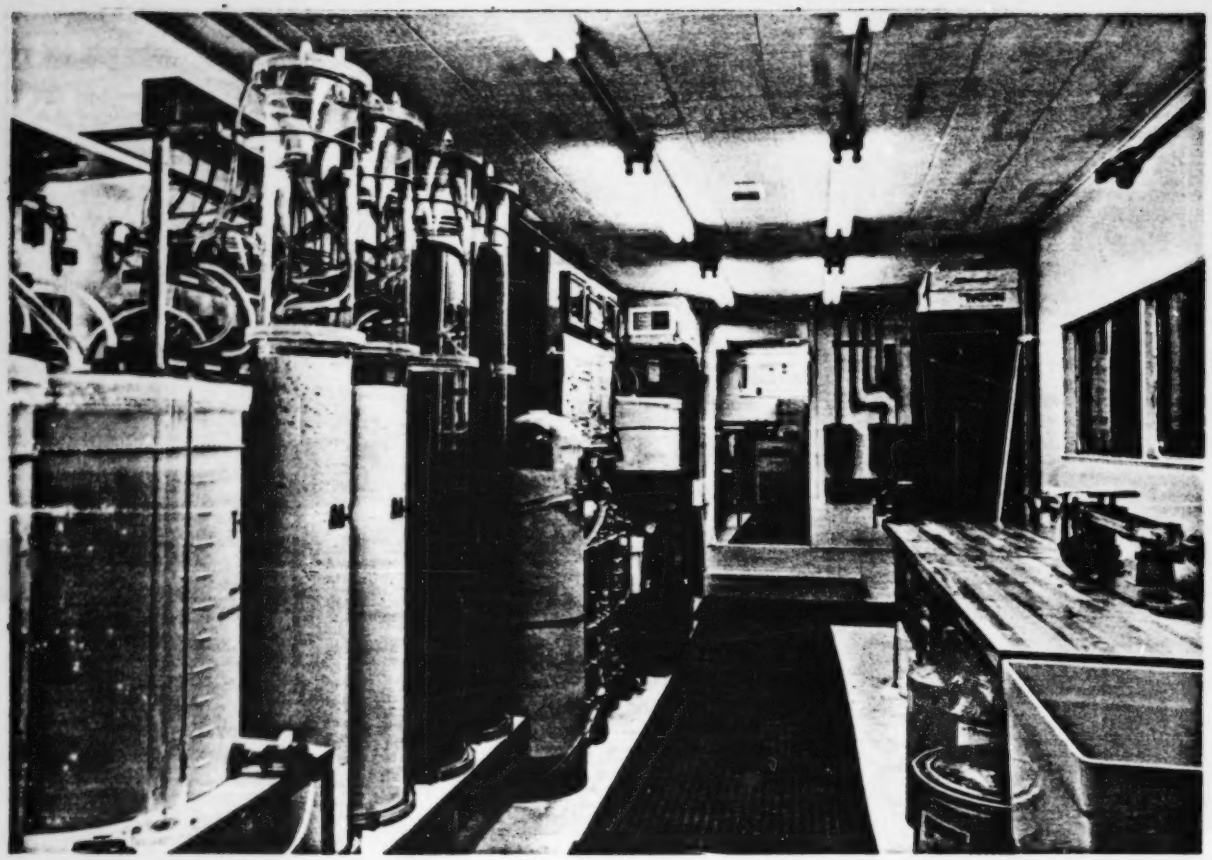


Figure 6. Pilot plant in Mobile Research Facility. Looking into trailer from rear to front, treatment processes on left, work and storage areas on right, door opened to laboratory in center of picture.

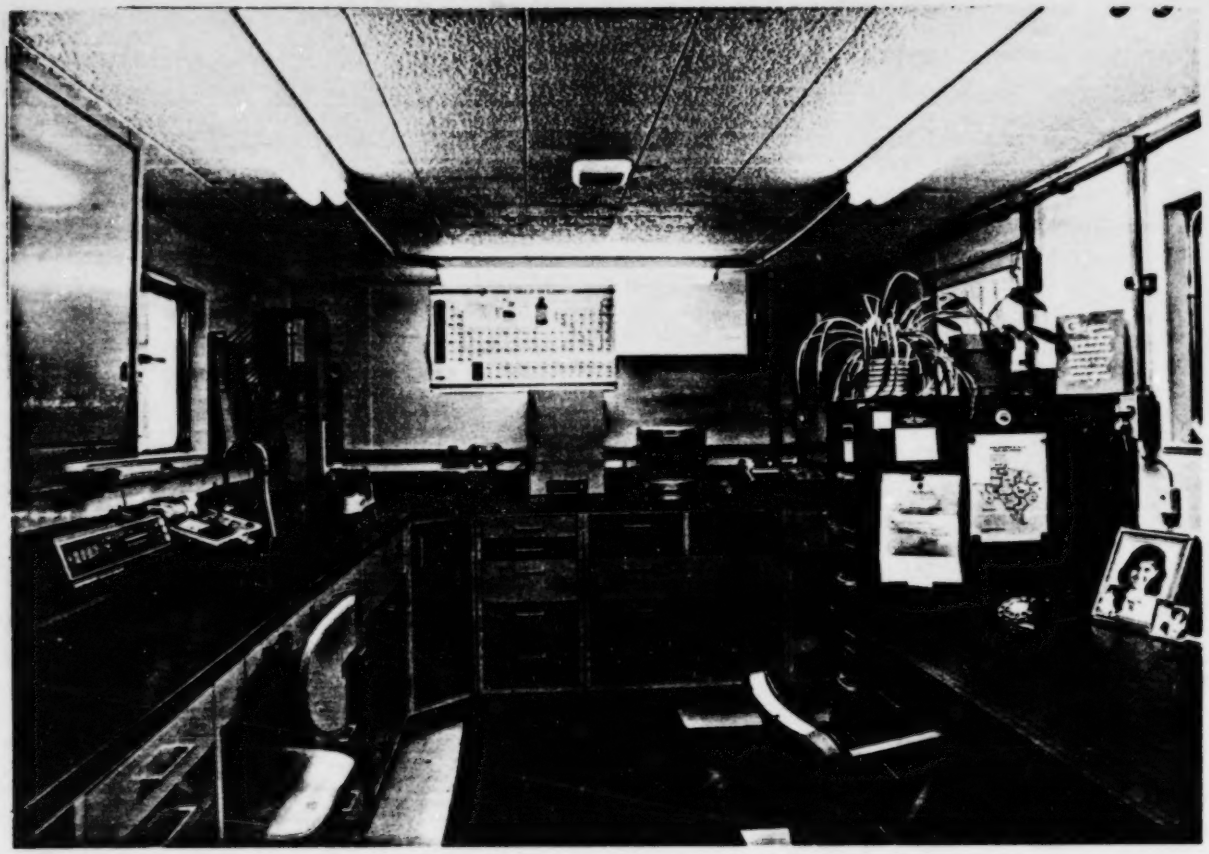


Figure 7. Laboratory in Mobile Research Facility. From left to right: sink with window above, drying rack, fume exhaust hood, entrance door, file and desk with window above.

pumps have been provided so that both the ion exchange and alumina systems may be regenerated or cleaned with acids, bases, or salts in any conceivable sequence.

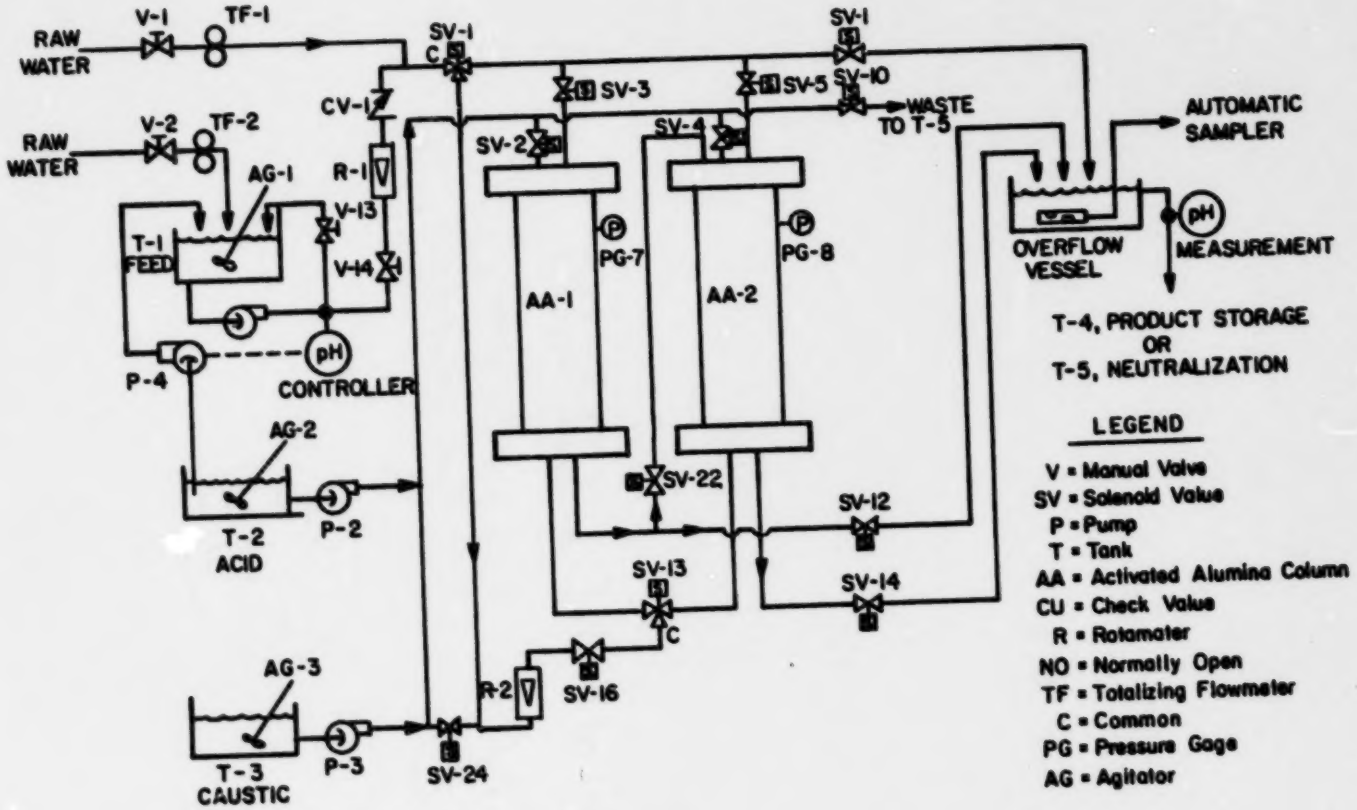
The reverse osmosis desalting system is made up of two different, standard, hollow-fiber modules which may only be operated one at a time. The Du Pont aramid module has a nominal product water flow of 1.45 gal/min (5.52 L/min) and operates at a typical feed pressure of 350 psig (2415 kPa) with a typical product water recovery of 50 percent. The Dow cellulose triacetate module is considerably larger, having a nominal product flow of 2.78 gal/min (10.5 L/min) also operating at 350 psig (2415 kPa) and 50 percent recovery. Both units have typical overall dissolved solids (TDS) rejections in the range of 95-98 percent and will be used to remove any contaminant ion of interest. As with the RO and IX units, the RO product water may be stored temporarily or disposed of locally with the reject brine. Proper pretreatment is known to be the key to successful RO system operation so the pilot plant has been designed with means for dechlorination, polymer addition, deep-bed filtration, and cartridge filtration.

The reversible electrodialysis (EDR) desalting system is the only system which was purchased as a complete unit from the manufacturer. The nominal product-water flow rate is 0.35 gal/min (1.31 L/min) and the % recovery is variable from 50-80 percent depending on the amount of brine recycle. As with the RO unit, the EDR unit will be used to study the removal of all contaminant ions of interest. Compared to RO, very little pretreatment is required for EDR and the system operates with only cartridge prefiltraton and dechlorination using an activated carbon filter. A membrane cleaning system using acids and/or chelating agents has been provided for cleaning the RO and EDR membranes as required.

ACTIVATED ALUMINA SYSTEM (Figures 8 and 9, Tables 5 and 6)

The detailed flow schematic of the two-column activated alumina system with upflow or downflow regeneration is shown in Figure 8. During column exhaustion, raw water flows into the pH-adjustment tank (T-1) through a level-control float valve mounted inside the tank near the top. Feedwater pH is adjusted by adding H_2SO_4 or HCl from acid tank T-2 using metering pump P-4 which is turned on or off by the feed pH controller. pH-adjusted raw water is pumped (P-1) at a controlled rate into alumina column AA-1 or AA-2 through rotameter R-1 by adjusting the bypass water flow (V-13). Either column may be operated separately or both columns may be operated in series by manipulating electrical solenoid valves SV-3, 5, 12, 14, and 22. Treated effluent from the alumina system passes through the overflow vessel where it is sampled by the auto sampler at fixed time intervals. Effluent from the overflow vessel is collected in either the treated water (T-4, T-6), or wastewater (T-5, T-7) tanks or wasted directly to the sewer.

After alumina column exhaustion, the media may be backwashed (a) using pumped (P-1) pH-adjusted raw or treated water by manipulating solenoid valves SV-1, 13, 16, 3, 5, and 11, or (b) using line pressure and raw water from V-1,



ACTIVATED ALUMINA FLOW SYSTEM

Figure 8. Process and instrumentation flow diagram for the dual column activated alumina adsorption system.

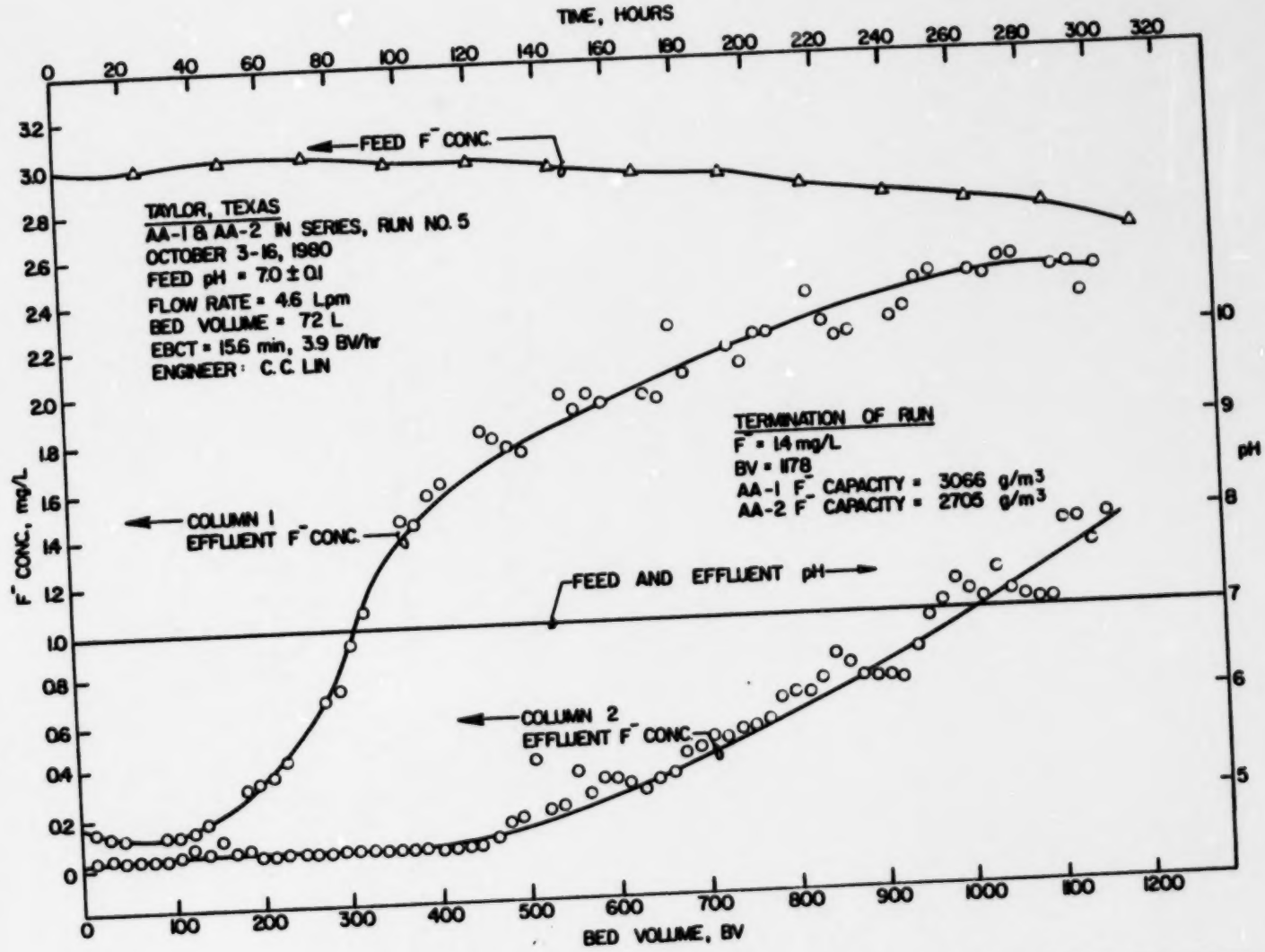


Figure 9. Fluoride breakthrough curves for a two-column activated alumina adsorption system containing 36 L of media per bed.

TABLE 5. TYPICAL ALUMINA SYSTEM SPECIFICATIONS

Column height = 6 ft, 1.83 m
Column inside diameter = 8 inches, 20.3 cm; wall thickness = 1/4 in, 0.635 cm
Depth of media = 3.64 ft., 1.11 m
Column cross-sectional area = 0.349 ft^2, 324 cm^2
Volume of media = 1.27 ft^3 = 36 L
Water flow rate = 2 gpm = 7.57 L/min
Column loading = 5.73 gpm/ft^2, 233 L/m^2 min
Empty bed contact time = 4.76 min
Exhaustion rate = 1.58 gpm/ft^3, 8.0 BV/hr
Regeneration rate = 1.62 L/min of 1% NaOH
Acidification rate = 1.49 L/min of 2% H_2SO_4
Backwash rate = 7.0 gpm/ft^2, 285 L/m^2 min using treated water
Typical F^- concentration = 5 ppm, 0.263 meq/l
Maximum adsorption capacity = 8500 g F^-/m^3, 0.447 eq/L
Typical run time = 3.0 days = 72 hours
Typical regeneration contact time = 90 minutes
Typical acidification contact time = 30 minutes

PUMPS

Acid metering pump for pH control: 0 - 100 mL/min, 10 psig
Acid and base metering pumps: 0 - 3 L/min, 10 psig
Feedwater-backwash pump: 5 gpm, 10 psig
Waste and treated water pumps: 5 gpm, 5 psig.

TABLE 6. ACTIVATED ALUMINA ADSORPTION (AA1): INDEPENDENT AND DEPENDENT VARIABLES TO BE STUDIED DURING FLUORIDE, ARSENIC, AND SELENIUM REMOVAL TESTS

Adsorption Step

Number of Columns in Series: 1 or 2
Media Depth: 1 m to 2 m
Size of Alumina Granules: 12 x 28 or 28 x 48 mesh
Empty Bed Contact Time: 3 min through 20 minutes
Constant, Stepwise or Variable Feedwater pH Adjustment
Effluent Concentration History of Contaminant: F^-, Se(IV), Se(VI), As(III), or As(V)
Effluent Concentration History of Aluminum, i.e., Extent of Dissolution of Media
Effluent Concentration Histories of Common Cations and Anions: Ca^{++}, Mg^{++}, Na^+, HCO_3^-, Cl^-, $SO_4^=$, and especially SiO_2
Fluoride Loading on Alumina at Bed Exhaustion: gm/m^3
pH of Effluent: Continuously Monitored
Effect of the Presence of Competing Ions, Especially Silicate

Regeneration Step

Regenerant alkali concentration: 0.5 - 4% NaOH; 4% NH_4OH
Regenerant flow direction: downflow or upflow
Regenerant contact time: 1 hr to 4 hrs
Single stage upflow or downflow regeneration
Reuse of spent regenerant for several regenerations
% recovery (elution) of adsorbed contaminant: F^-, As(III), As(V), Se(IV), Se(VI)
% recovery of adsorption capacity after regeneration
Method of Acidifying Bed after NaOH Regeneration
Acid Used for Acidification of Alkali Regenerated Bed: H_2SO_4, HCl
Acidification Step Acid Concentration: 0.125 to 1.0 N H_2SO_4 (0.5 to 5%)

by manipulating SV-1, 13, 3, 5, and 11. Downflow alkaline regeneration is accomplished with caustic solution pumped (P-3) from tank (T-3) into one or the other of the columns by manipulating solenoid valves SV-2, 12, 4, and 14. Spent regenerant passes through the overflow vessel where it is sampled by the autosampler before being collected in the neutralization tank where it is held for neutralization by spent acid. Upflow regeneration is accomplished with caustic pumped (P-3) through SV-24 and then into AA-1 (or AA-2) by manipulating SV-16, 13, 2, 4, and 10. Displacement (slow) rinsing of the caustic from the columns may be accomplished using raw or treated water pumped (P-2 or P-3) from either tank T-2 or T-3 at the same rate through the the same valves as the caustic regenerant.

Acidification of the columns following caustic regeneration may be done using a stepwise pH-adjustment of the feedwater through the usual exhaustion flow system or by pumping (P-2) acid from tank T-2 through the same valves as were used for the caustic regeneration.

The usual activated alumina operating sequence is as follows: exhaustion, backwash, caustic regeneration (downflow or upflow), displacement rinse, acidification, repeat. Detailed specifications of the activated alumina system are given in Table 5 and a complete listing of the variables to be studied during the field research is given in Table 6. The operation of two alumina beds in series to remove 3.0 mg/L fluoride from 1100 mg/L TDS Taylor, Texas groundwater is illustrated in Figure 9. It can be seen in that figure that the effluent fluoride concentration from the first column reaches the MCL of 1.4 mg/L at about 350 bed volumes (BV) of water throughput while the second column achieves about 1170 BV before the MCL is reached. By operating the columns in series, the fluoride capacity of the first column is improved (3066 g/m^3) compared to the second column (2705 g/m^3).

ION EXCHANGE SYSTEM (Figures 10 and 11; Tables 7, 8, and 9)

With the exception of a larger column diameter (10 in dia), the two-column ion exchange system is nearly identical in design to the activated alumina system just described. In fact, ion exchange resins and activated alumina may be used interchangeably in any of the columns. Normally, a single strong-base anion exchange column will be used for the ion-exchange research but provisions have been made for serial two-bed anion/anion or cation/anion system operation using IX-1 and IX-2 or AA1-1 and AA1-2. As with the activated alumina system, regeneration may be either downflow or upflow.

For exhaustion of a single anion column (Figure 9), raw water is pumped (P-1) from tank T-1 downflow through either column (IX-1 or IX-2) by manipulating valves V-13 and V-14 to control flow and solenoid valves SV-7, 9, 18, and 20 to direct the flow through IX-1 or IX-2 into the overflow vessel and finally into one of the collection tanks (T-4 or T-5). The automatic sampler withdraws samples from the overflow vessel at a predetermined time interval, e.g., hourly, and stores the samples for subsequent analyses and construction of effluent concentration histories of eluted ions.

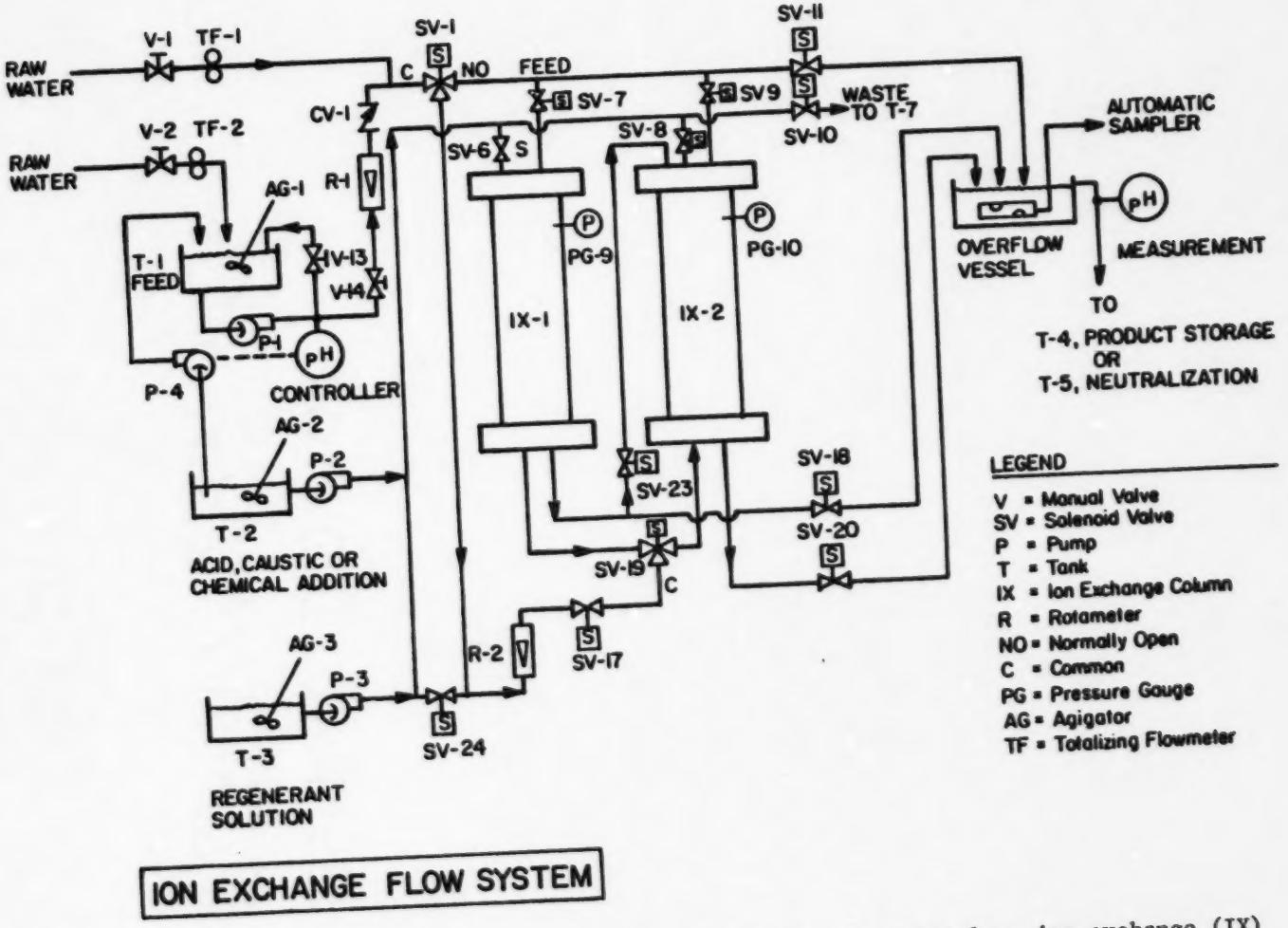


Figure 10. Process and instrumentation diagram for the two-column ion exchange (IX) system.

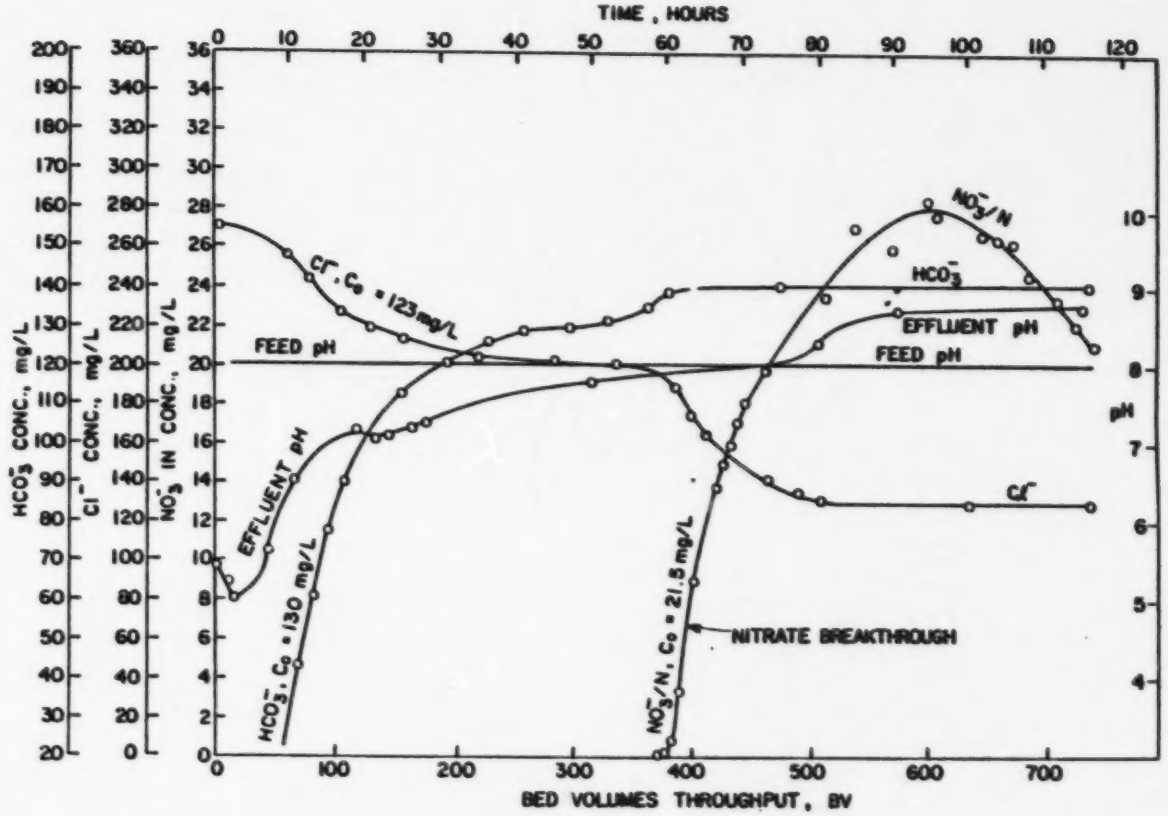


Figure 11. Breakthrough curves for nitrate and other ions emanating from a single bed of chloride-form anion-exchange resin used to remove nitrate from Glendale, AZ ground water.

TABLE 7. TYPICAL ION EXCHANGE SYSTEM SPECIFICATIONS

Column height = 6 ft, 1.83 m
Column inside diameter = 10 inches; wall thickness = 1/4"
Depth of media = 3.12 ft., 0.951 m
Column cross-sectional area = 0.545 ft^2, 0.0506 m^2
Volume of resin = 1.70 ft^3, 48.1 L
Water flow rate = 2 gpm, 7.57 L/min
Column loading = 3.67 gal/min ft^2, 150 L/m^2min
Empty bed contact time = 6.36 min
Exhaustion rate = 1.05 gal/min ft^3, 8.4 BV/hr
Anion exchange capacity = 1.4 meq/mL resin
Typical run time = 24 hours
Backwash rate = 3 gal/min ft^2, 224 L/m^2 min
Regeneration rate = 0.350 gal/min ft^3, 0.047 L/min L
Regenerant contact time = 21.5 min
Regeneration time = 60 - 90 min
Displacement rinse rate = 0.35 gal/min ft^3, 0.047 L/min L
Displacement rinse volume = 2 BV
Fast rinse rate = 2 gpm, 7.57 L/min
Fast rinse volume = 10 - 20 BV

TABLE 8. SINGLE ANION BED ION-EXCHANGE (IX): INDEPENDENT AND DEPENDENT VARIABLES TO BE STUDIED DURING NITRATE, ARSENIC, AND SELENIUM REMOVAL TESTS

Exhaustion Step

Strong base anion resin characteristis:

(1) Dowex 11, STY-DVB, Quat. Type 1, Isoporous SBA, $\alpha S/N = 3.4$, $\alpha N/Cl = 3.0$

(2) Ionac ASB-II, STY-DVB, Quat. Type 2, Gel SBA, $\alpha S/N = 3.0$, $\alpha N/Cl = 3.6$

(3) Ionac ASB-I, STY-DVB, Quat. Type 1, Gel SBA, $\alpha S/N = 1.87$, $\alpha N/Cl = 3.0$

Number of columns in series: 1 or 2
Media depth: 0.6m to 2 m in AA or IX columns
Empty bed contact time: 1 min to 10 min
Effluent concentration history of contaminant: NO_3^-, As(III), As(V), Se(IV), Se(VI)
Effluent concentration histories of all common ions: Ca^{++}, Mg^{++}, Na^+, Cl^-, HCO_3^-, $SO_4^=$, and SiO_2
pH of effluent: continuously monitored
Contaminant loading on bed at contaminant breakthrough: meq NO_3^-/mL
Degree of resin fouling observed due to: Fe, Mn, SiO_2

Regeneration Step

Regenerant flow direction: downflow or upflow
Regenerant NaCl concentraton: 1.0 to 4.0 N (6% to 24%)
% Recovery (elution) of "sorbed" contaminant: F, As(III), As(V), Se(IV), Se(VI)
% Recovery of ion exchange capacity after regeneration
Stoichiometry of regeneraion: meq regenerant/meq contaminant removed
Quantity and compostion of regenerants produced

Notes:

$\alpha S/N$ = Sulfate/Nitrate Separation Factor
$\alpha N/Cl$ = Nitrate/Chloride Separation Factor
STY-DVB = Strene Divinylbenzene
SBA = Strong Base Anion
WBA = Weak Base Anion
Quat. = Quaternary amine anion resin

TABLE 9. TWO-BED ION EXCHANGE (IX):
INDEPENDENT AND DEPENDENT VARIABLES TO BE STUDIED
DURING NITRATE, ARSENIC, AND SELENIUM REMOVAL TESTS

Exhaustion Step

Strong acid cation resin characteristics: only one resin to be used in the studies: STY-DVB sulfonic acid type, Duolite C-20, 2.0 meq/mL

Weak-base anion resin characteristics:

(1) Amberlite IRA-45, STY-DVB, Tertiary Amine, Gel, WBA, $\alpha S/N$ = 13, $\alpha N/Cl$ = 3.9, 1.8 meq/mL

(2) Duolite ES 374, Polyacrylic, Polymine, Macroporous SBA, $\alpha S/N$ = 94, $\alpha N/Cl$ = 3.9, 2.6 meq/mL

(3) Dowex WGR; Epoxy-Amine Polyamine, Gel, WBA, $\alpha S/N$ = 140; $\alpha N/Cl$ = 2.0, 1.5 meq/mL

(4) Amberlite IRA-68, Polyacrylic Tertiary Amine, Gel, WBA $\alpha S/N$ = 23; $\alpha N/Cl$ = 1.9, 1.4 meq/mL

Media depth: 0.6 m to 2 m for anion bed
Number of cation columns in series: 1 or 2
Number of anion columns in series: 1 or 2
Empty bed contact time: 1 to 10 minutes
Effluent concentraton history of contaminants: NO_3^-, As(III), As(V), Se(IV), Se(VI)
Effluent concentration history of all common ions: Ca^{++}, Mg^{++}, Na^+, Cl^-, HCO_3^-, $SO_4^=$
pH of column effluent: continuously monitored
Contaminant loading on bed at contaminant breakthrough: meq/mL
Degree of resin fouling observed due to: Fe, Mn, SiO_2, organics

Regeneration Step

Cation regenerant used: 0.5 to 2 N H_2SO_4 or HCl
Anion regenerant used: 1.0 to 2.0 N NH_4OH (3.5 - 7.0% NH_4OH)
Cation regeneration level: 1 - 5 meq regenernt/meq resin
Upflow or downflow regeneration: primarily for cation bed
Neutralizaton requirements for spent regenerants
Chemical composition of spent regenerants
Disposition of spent regenerants: land vs sewer disposal

Notes:
$\alpha S/N$ = Sulfate/nitrate separation factor
$\alpha N/Cl$ = Nitrate/chloride separation factor
STY-DVB = Styrene divinylbenzene
SBA = Strong base anion
WBA = Weak base anion

Backwashing an exhausted column may be accomplished with pressurized raw water (V-1) or pumped (P-1) treated water which has been returned to the feed tank T-1 from one of the treated water storage tanks (T-4 or T-6). To direct the backwash flow through one or the other columns into the overflow vessel and then to waste, electrical solenoid valves SV-17, 19, 7, 9, and 11 are manipulated.

The downflow regeneration and displacement rinse flow patterns are from tanks T-3 or T-2 through pumps P-3 or P-2 into and through IX-1 or IX-2 to the overflow vessel where sampling takes place. The downflow regenerant and displacement rinse flows are directed using solenoid valves SV-6, 8, 18, and 20. Upflow regeneration may be accomplished from tanks T-2 or T-3 using pumps P-2 or P-3 then directing the regenerant flow through IX-1 or IX-2 to the overflow vessel by manipulating SV-24, 17, 19, 6, 8, and 10.

In order to exhaust two anion (or cation) beds in downflow series, the flow pattern is from tank T-1 through pump P-1 and solenoid valves SV-1, 7, 23, and 20 in sequence and then into the overflow vessel. The same downflow exhaustion flow pattern is used for a two-bed strong-acid, weak-base system. However, in this case, the acid (cation) regeneration would take place downflow or upflow from tank T-2 and the alkaline (anion) regeneration from tank T-3. Figure 11 depicts effluent concentration histories for pH, HCO_3^-, Cl^-, and NO_3-N during a single-bed anion column run in Glendale, Arizona to remove nitrate from a 500 mg/L TDS well water. There it is seen that the column may be run for a respectable length of time and that nitrate breaks through at approximately 400 bed volumes of throughput. It should also be noted that after breakthrough of nitrate, its maximum concentration (25 mg/L NO_3-N) is higher than the feedwater nitrate concentration (22 mg/L NO_3-N).

The usual ion exchange column operating sequence is as follows: exhaustion, backwash, regeneration (upflow or downflow), displacement (slow) rinse, fast rinse, repeat. The fast rinse, not previously described, is accomplished in the same manner as the exhaustion step except that the rinse water is sent to waste rather than treated water storage.

Detailed specifications for the ion-exchange system are listed in Table 7 and the variables to be studied during single-anion bed research and two-bed (cation/anion) research are listed in Tables 8 and 9 respectively.

REVERSE OSMOSIS SYSTEM (Figure 12 and 13; Tables 10 - 13)

The RO system features two single-pass hollow-fiber modules--one with cellulose triacetate membranes (Dowex, RO-4K) and the other with aramid membranes (duPont B9). Only one module is operated during a given test which is usually run for 100 hours at 50-60% conversion to determine the rejections of the various ions in the feed. Prior to actual system operation, the optimum pH, pretreatment requirements, and estimated % rejections are determined using a computer program (by Dow or duPont) which makes use of the complete chemical analysis of the raw water including its temperature. Examples of a feed water analysis and a computer prediction for operation of the Dowex 4K Module on

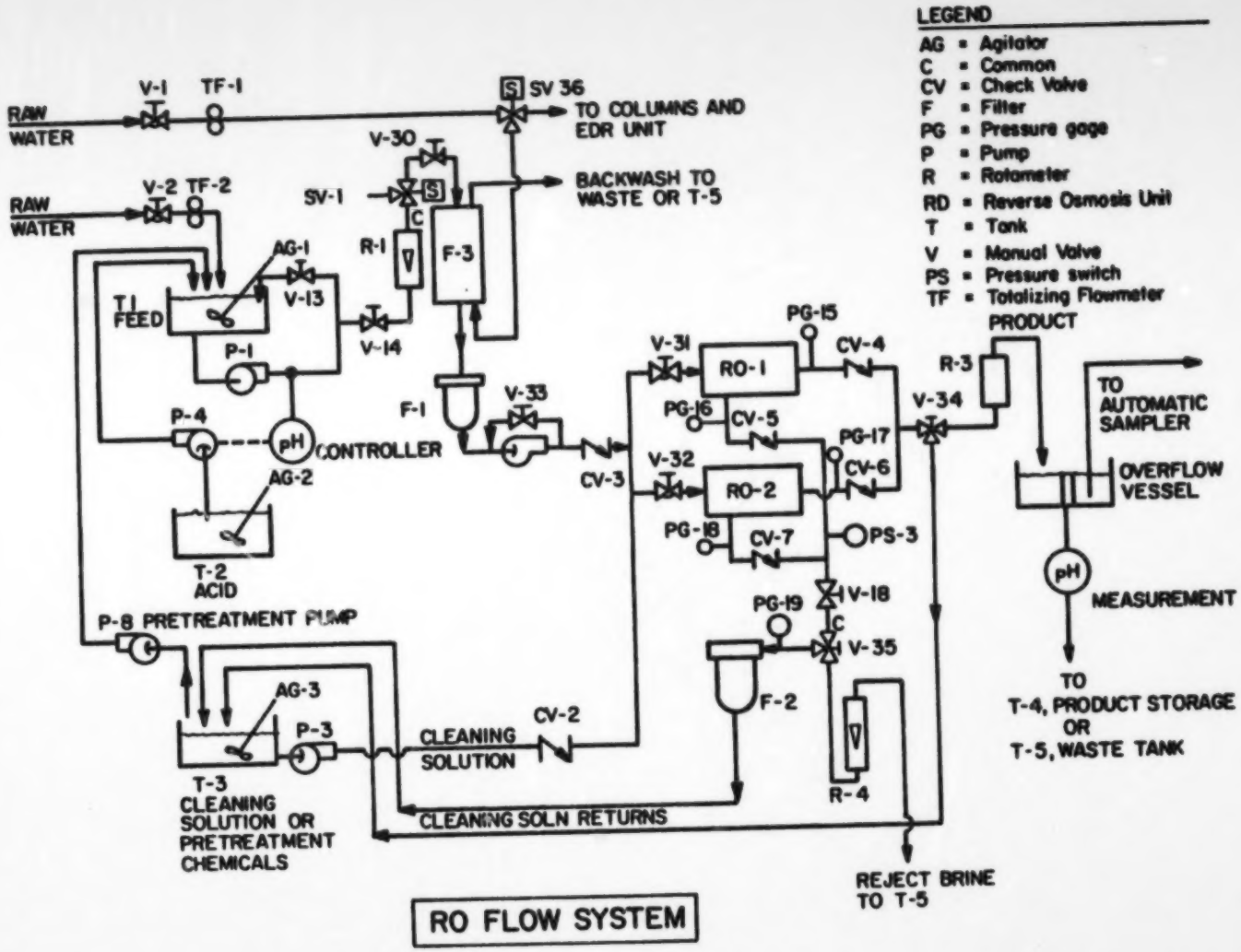


Figure 12. Process and instrumentation diagram for the reverse osmosis (RO) system.

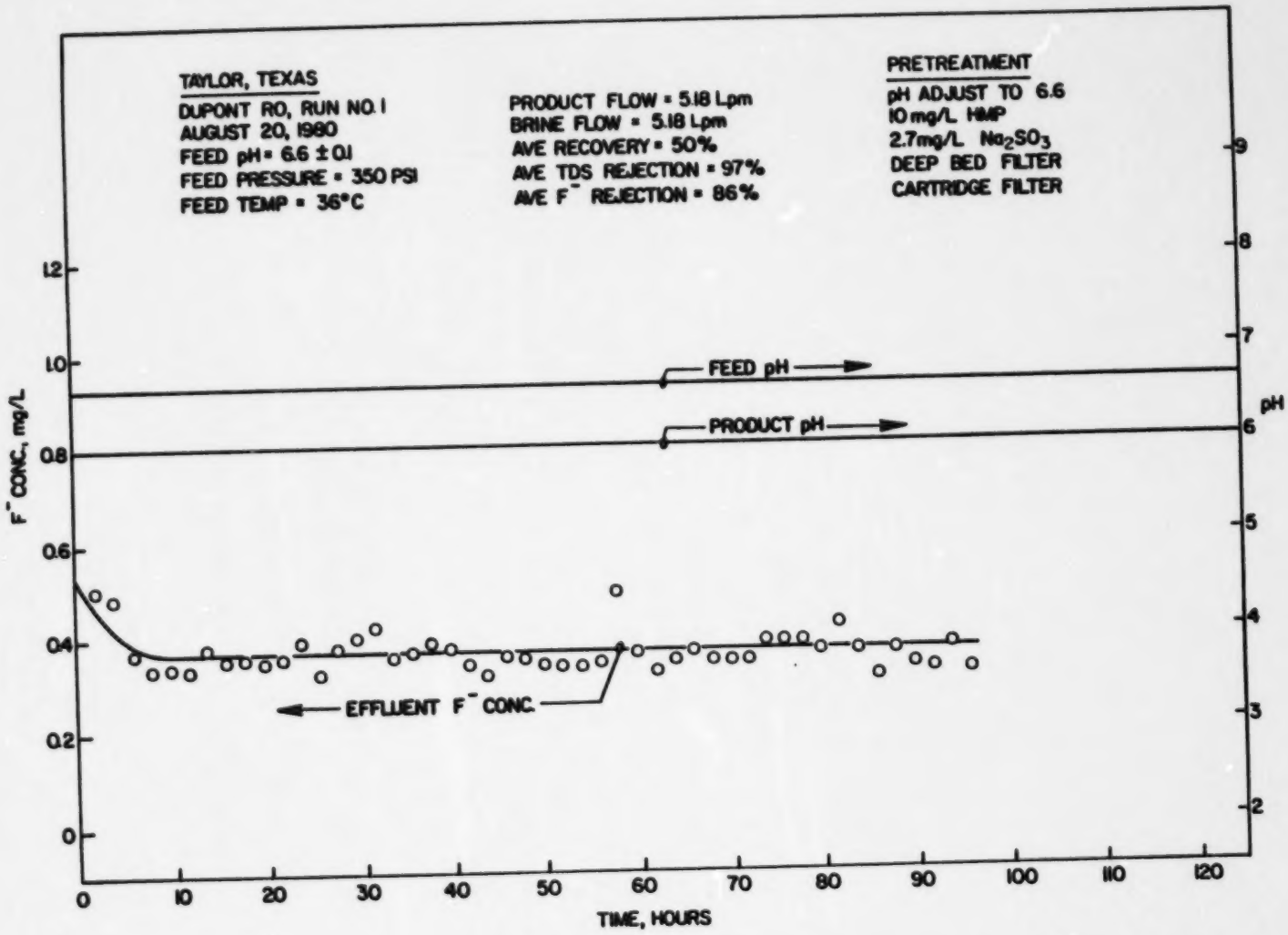


Figure 13. Fluoride concentration and pHs for a typical RO run on Taylor, TX ground water containing 1100 mg/L TDS and 3.0 mg/L fluoride.

TABLE 10. RAW WATER ANALYSIS FOR WELL NO. 1, GLENDALE, ARIZONA

Contaminant Concentration	Concentration mg/L	Concentration meq/L
pH	8.0	
Conductivity (μmho cm)	820	
Silt Density Index (SDI)	5.6	
Total Dissolved Solids	532	
Total Suspended Solids	5.7	
Silica (SiO_2)	23.1	
ANIONS		
Total Alk ($CaCO_3$)	102	
NO_3-N	18.6	1.33
F^-	0.52	0.03
Cl^-	122.5	3.45
$SO_4^=$	42.5	0.89
HCO_3^-	124	2.03
	meq anions	7.73
CATIONS		
Total Hardness ($CaCO_3$)	198	
Ca^{++}	43	2.15
Mg^{++}	28	2.30
Na^+	76	3.30
Fe^{++}	0.26	0.01
	meq cations	7.76

TABLE 11
DOWEX* P.D. PERMEATOR SYSTEM DESIGN
UNIVERSITY OF HOUSTON

A 1 STAGE SYSTEM WITH 1 PERMEATORS (STD. TEST PERFORMANCE OF 4000.GPD, 90.0% REJECTION) OPERATING AT 400. PSI AND INTERSTAGE PRESSURE LOSS OF 0. PSI. OVERALL SYSTEM RECOVERY IS 50.0 %. DESIGN FEED TEMPERATURE IS 35.0 DEG.C.

ASSUMPTIONS: STERILE FEEDWATER, INJECTION OF APPROPRIATE SCALE INHIBITOR AND ACIDIFICATION FOR CARBONATE SCALE CTRL: 0.29 LBS H2SO4(100 PCT)/KGAL FEED

WATER ANALYSIS

ION	PPM ION IN RAW FEED	PPM ION IN TREATED FEED	PPM CACO3 IN TREATED FEED	PPM ION IN PERMEATE	PPM ION IN CONCENTRATE
CA++	46.00	46.00	115.00	1.29	90.71
NA+	76.00	76.00	165.68	6.17	145.83
MG++	28.00	28.00	115.08	0.63	55.37
FE++	0.10	0.10	0.18	0.00	0.20
MN++	0.00	0.00	0.00	0.00	0.00
K+	0.00	0.00	0.00	0.00	0.00
TOT+	150.10	150.10	395.94	8.10	292.10
CL-	131.00	131.00	184.51	3.30	258.70
F-	0.50	0.50	1.32	0.02	0.98
SO4--	43.00	76.50	79.69	1.47	151.54
NO3-	97.40	97.40	78.89	12.30	182.50
SIO2	23.00	23.00	38.41	1.60	44.40
PO4---	0.00	0.00	0.00	0.00	0.00
HCO3-	124.00	81.49	66.80	3.73	159.25
CO3--	0.00	0.00	0.00	0.00	0.00
TOT-	418.90	386.89	411.20	20.81	752.98
GRAND TOTAL	569.00	559.99	441.98	30.50	1089.48
PH	8.00	6.60		5.75	6.81
CO2		33.42		25.07	
LANGELIER INDEX					-0.26

OPTIMIZED DESIGN CONFIGURATION AND RATINGS

STAGE NO.	PERMEATORS PER STAGE	AVG. UNIT PROD.(GPD)	TOTAL PROD. FLOW(GPD)	TOTAL BRINE FLOW(GPD)	PCT. REC.	PCT. REJ.	DELTA (PSI)
1	1	5846.	5846.	5846.	50.00		5.
OVERALL	1	5846.	5846.	5846.	50.00	94.55	

MAXIMUM RECOVERY TO AVOID SATURATION WITH:

GYPSUM	100.0 PERCENT	CASO4 ANHYDRITE	100.0 PERCENT
BARIUM SULFATE	100.0 PERCENT	STRONTIUM SULFATE	100.0 PERCENT
	SILICON DIOXIDE	81.4 PERCENT	

THIS ESTIMATE OF AN APPROPRIATE DESIGN CONFIGURATION AND EXPECTED PERFORMANCE OF DOWEX* P.D. PERMEATORS IS BASED UPON THE PARTICULAR FEEDWATER ANALYSIS SUBMITTED TO THE DOW CHEMICAL CO. THE DESIGN AND EXPECTED PERFORMANCE ARE PRESENTED IN GOOD FAITH, BUT NO WARRANTY IS EXPRESSED OR IMPLIED. ALTHOUGH THESE CRITERIA SHOULD ASSURE PROPER PERFORMANCE OF THE DOWEX* P.D. PERMEATORS, THE ULTIMATE SUCCESS OF ANY P.D. FACILITY DEPENDS UPON AN ADEQUATELY ENGINEERED SYSTEM THAT IS PROPERLY OPERATED AND MAINTAINED.

* TRADEMARK OF THE DOW CHEMICAL COMPANY

TABLE 12. REVERSE OSMOSIS SYSTEM SPECIFICATIONS

Number of Modules: Two in parallel
Mode of Operation: Module 1 or Module 2

Module 1: duPont Model No. 0420-21
- Membrane Type: B-9 Aramid
- Membrane Configuration: Hollow Fiber
- Shell Dimensions: 13.3 cm OD x 63.5 cm long (5.25 in OD x 25 in long)
- Product Water Capacity: 7.95 m^3/day (2,100 gpd at 1500 ppm TDS)
- Operating Pressure: 0-2760 kPa (0-400 psig)
- Operating Temperature: 0-35°C (32-95°F)
- pH Range, Continuous: 4-11
- Minimum Brine Rate: 4.2 L/min (1.11 gpm)
- Chlorine Tolerance: Cl_2 must be removed
- Silt Density Index, SDI: ≤ 3.0

Module 2: Dow Model Dowex 4K
- Membrane Type: Cellulose Triacetate
- Memrane Configuration: Hollow Fiber
- Shell Dimensions: 15.88 cm OD x 122 cm long (6.25 in OD x 48 in long)
- Product Water Capacity: 15.14 m^3/day (4,000 gpd at 1500 ppm TDS)
- Operating Pressure: 0-2760 kPa (0-400 psig)
- Operating Temperature: 0-30°C (32-86°F)
- pH Range, Continuous: 4.0 - 7.5
- Minimum Brine Rate: 1.9 L/min (0.5 gpm)
- Chlorine Tolerance: ≤ 1.0 mg/L
- Silt Density Index, SDI: ≤ 4.0

RO Pump: Moyno 9P3, 316 ss Rotor
- Maximum Pump Pressure; 5520 kPa (800 psig)
- Pump Operaing Pressure; 2760 kPa (400 psig)
- Pump Motor: 3 hp, 220 v, Single Phase
- High Pressure Cutoff: 3105 kPa (450 psig)
- High Pressure Relief: 3105 kPa (450 psig)
- Low Pressure Cutoff: 2070 kPa (300 psig)

RO Pretreatment Filters: Two Provided--One Deep Bed, One 10 Cartridge
- Deep Bed Filter: 35.6 cm OD x 165 cm height (14 in OD x 65 in height)
- Filter Media: 76.2 cm AG over 10 cm flint gravel (30 in AG over 4 in flint gravel)
- Filtration Rate: 117-293 m/day (2 - 5 gal/min ft^2)

TABLE 13. REVERSE OSMOSIS (RO): INDEPENDENT AND DEPENDENT VARIABLES TO BE STUDIED DURING REMOVAL OF FLUORIDE, NITRATE, ARSENIC, AND SELENIUM

Membrane material: hollow fiber aramid (duPont), or cellulose triacetate (Dow)

Method of reducing fouling index of feed: deep bed filtration with "AG" media or "Electromedia"; AG media with and without polymer addition

Dechlorination methods: Na_2SO_3, granular activated carbon

Feedwater additives to prevent ppt of $CaCO_3$: Polyphosphates

pH of feedwater: adjusted by H_2SO_4 or HCl addition

pH of product water: continuous monitoring

Feedwater pressure: 1379 to 3447 kPa (200-500 psig)

% TDS removal: based on conductivity and gravimetric methods

% water recovery: (Product flow/feed flow)100; 40-60%

% rejection of contaminants: $[(C_F - C_P)/C_F]100$

% rejection of common ions: Ca^{++}, Mg^{++}, Na^{+}, Cl^{-}, HCO_3^{-}, $SO_4^{=}$, SiO_2

Various methods of cleaning membranes: H_2SO_4, HCl, citric acid, TSP; chelants such as VERSENE or EDTA; HClO, BIZ, etc

Notes:

C_F = Concentration of ion in feed
C_P = Concentration of ion in product

Glendale, Arizona well water are presented as Tables 10 and 11 respectively. Tables 12 and 13 summarize the reverse osmosis system design specifications and variables to be studied during the field research.

Acid (H_2SO_4) addition for the prevention of brine-side $CaCO_3$ precipitation is usually a required pretreatment for RO so pH adjustment by acid from tank T-2 is provided in the usual RO flow scheme. Additional provisions have been made for metering Na_2SO_3, sodium hexametaphosphate (HMP) and polyelectrolytes from tank T-3 into the raw water tank T-1 for dechlorination, scale control, and solids removal respectively.

pH-adjusted water containing the required additives is forced through the deep-bed, AG-media filter F-3 and the 10- m cartridge filter F-1 using a combination of the discharge pressure of the centrifugal feedwater pump P-1 and the suction from the 9-stage, Moyno, RO feedwater pump P-5. Control of the feed pressure, flow rate, and % recovery from Module RO-1 or RO-2 are achieved by adjusting the RO pump bypass valve V-33 and the brine discharge V-18. Brine is discharged into the waste tank T-5 while the product water flows through the overflow vessel from which it is sampled at a predetermined time interval by the automatic sampler.

Should a module become fouled due to $CaCO_3$, metal oxides, or bacterial slimes, it may be cleaned by pumping an appropriate cleaning solution from tank T-3 through the affected module for up to four hours at the maximum rate of pump P-3 with the pressure regulating valve V-18 wide open. The initial 20% of the effluent cleaning solution is wasted and the remainder is recycled from the brine and product lines to tank T-3 by manipulating the three-way selector valves V-35 and V-34.

Figure 13 is an example of the operation of the duPont RO module to achieve desalting and fluoride removal from a 3.0 mg/L fluoride, 1100 mg/L TDS feedwater in Taylor, Texas. The feedwater pH was adjusted to 6.6 with H_2SO_4; 10 mg/L HMP was added for scale control and the water was dechlorinated using sodium sulfite. During the 100-hour run, the average % product recovery was 50%, while the overall dissolved solids rejection was 97% and fluoride rejection averaged 86%.

ELECTRODIALYSIS SYSTEM (Figures 14-16; Tables 14 and 15)

The reversible electrodialysis unit is the only process in the research trailer which was purchased essentially as a complete unit (Aquamite I) from the manufacturer (Ionics, Inc.). That was done because the package unit was the only electrodialysis device commercially available in pilot scale. Figure 14 illustrates how the package unit was incorporated into the overall process flow system. It is not a complete flow schematic because within the EDR unit there are many additional components. In fact, there is another complicated flow system which is shown schematiclly in Figure 15 and described in Table 14.

Desalting and contaminant removal at 50-80% recovery are achieved by feeding pressurized raw water, usually without pretreatment or scale control

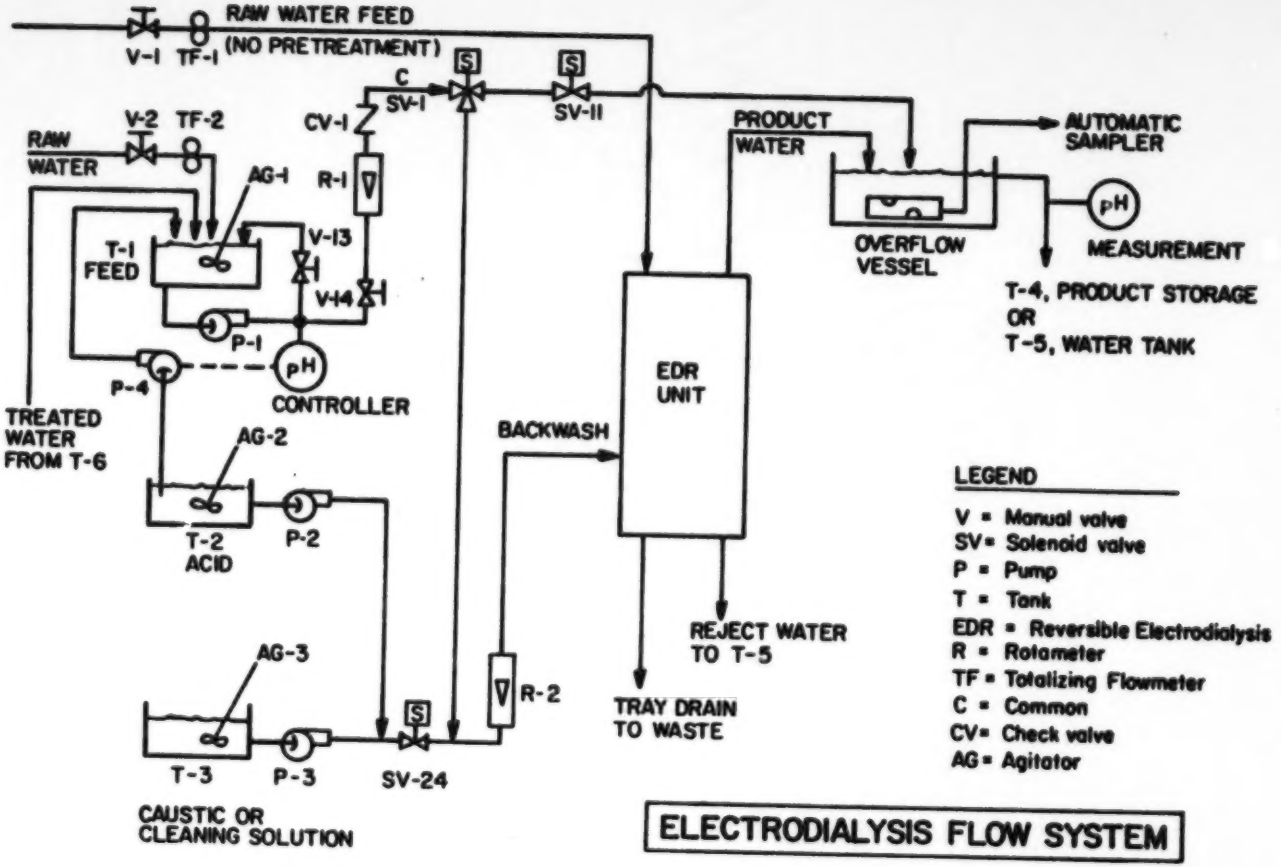


Figure 14. Process and instrumentation diagram for the reversible electrodialysis (EDR) system.

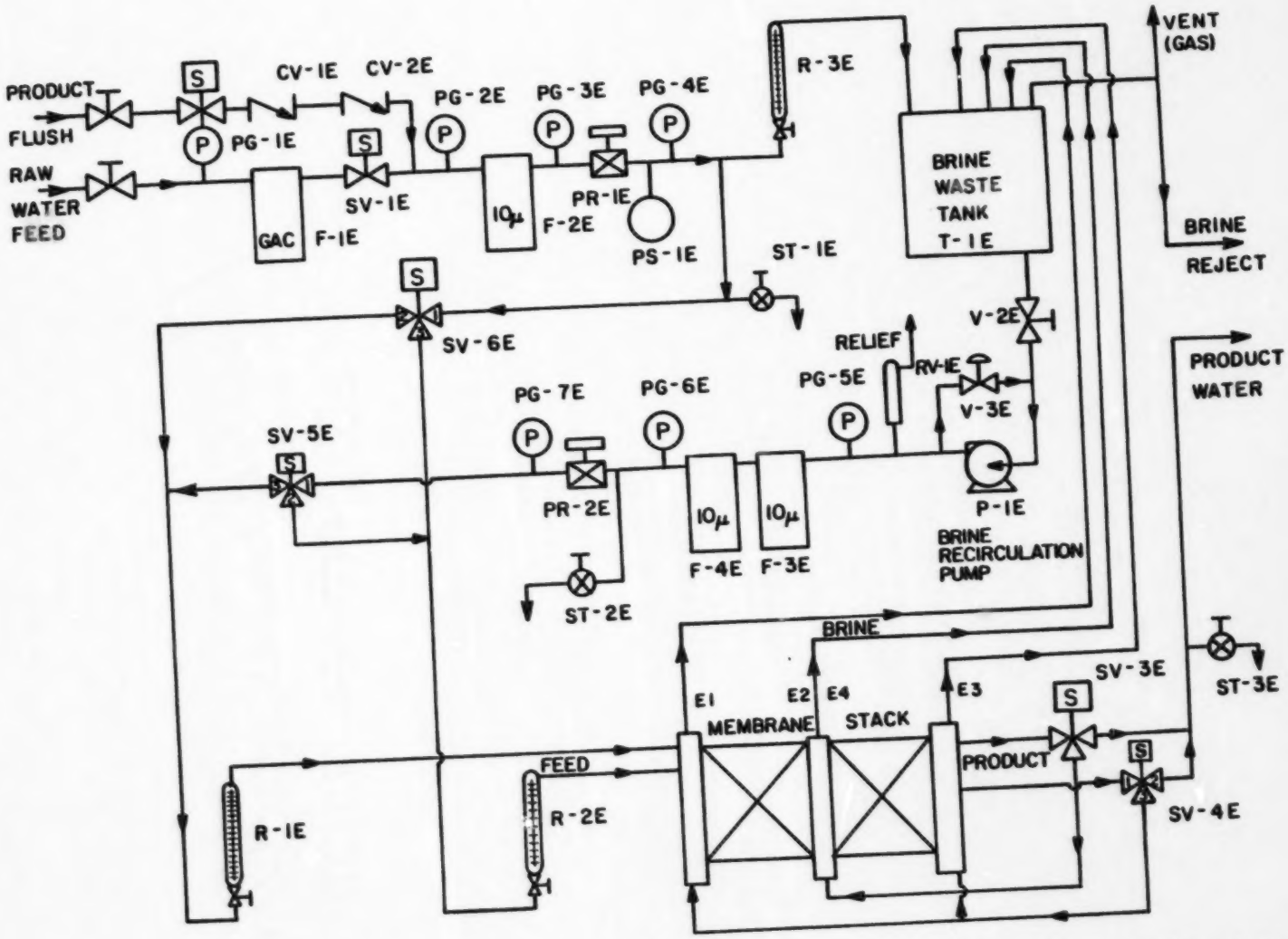


Figure 15. Internal flow schematic for the Ionics EDR unit shown in Figures 14 and 25.

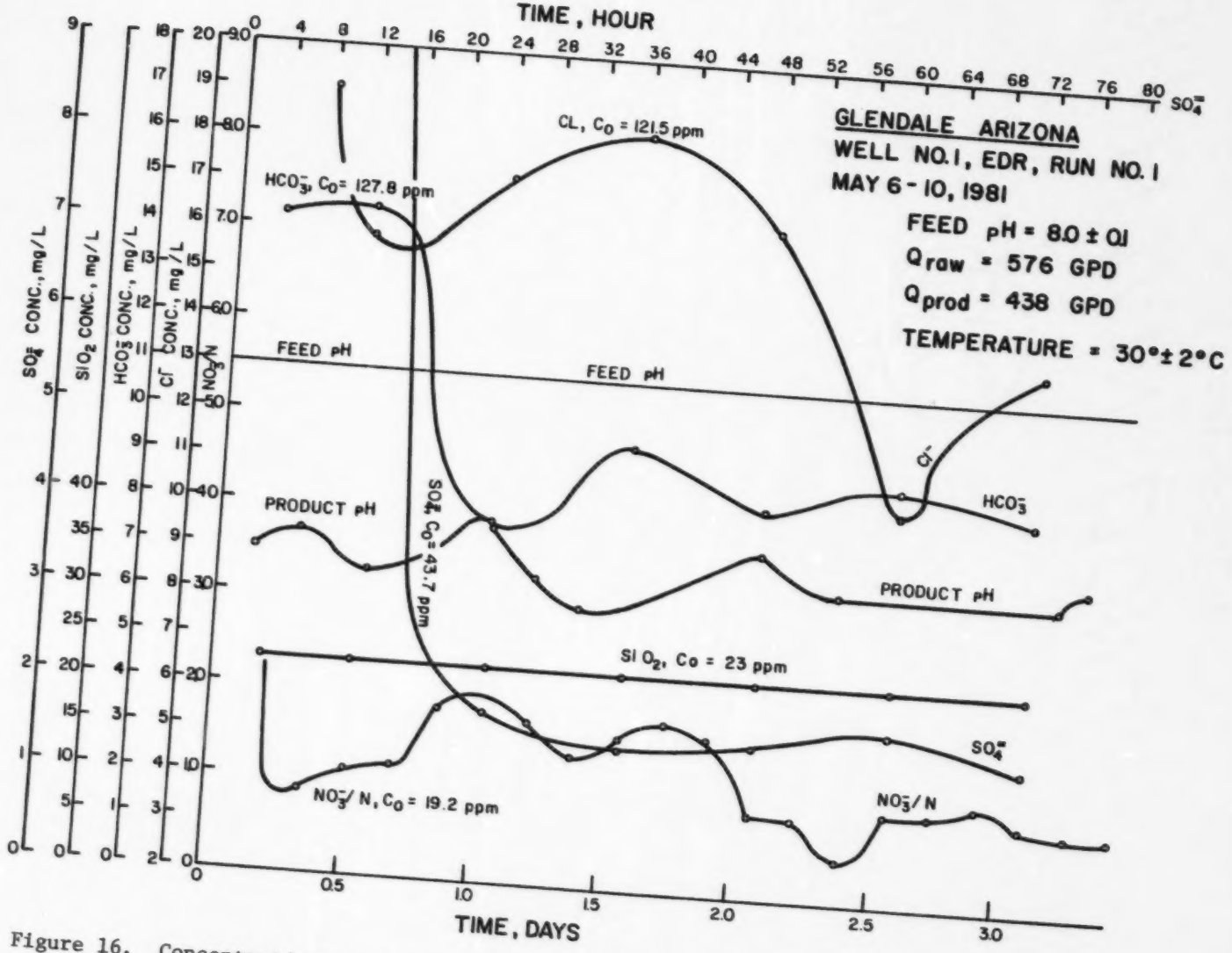


Figure 16. Concentration histories for nitrate and other ions in the EDR product water at Glendale, AZ during a typical nitrate removal/desalting run.

TABLE 14. REVERSIBLE ELECTRODIALYSIS SYSTEM SPECIFICATIONS

Manufacturer:	Ionics, Inc., Aquamite I
Pairs of Membranes:	200
Number of Hydraulic Stages:	6 in series
Stack Dimensions:	40.6 cm long x 24.1 cm wide x 30.5 cm high (16 in long x 9.5 in wide x 12 in high)
Product Flow:	1.9 m^3/day (500 gal/day at 2500 mg/L TDS feed)
Typical Product TDS:	100 mg/L at 50% recovery, 2500 mg/L TDS feed
% Recovery:	50 percent without brine recycle 80 percent with brine recycle
Polarity Reversal:	Once each 15 minutes
Power Characteristics:	120V, Single Phase
Power Consumption:	8 kWhr/1000 gal
Temperaure Range:	0-45°C (32-110°F)
Operating Pressure:	311 kPa (45 psig)
Stack Pressure Drop:	173 kPa (25 psig)
pH Range:	1 - 13
Chlorine Tolerance:	Cl_2 must be removed
Filter:	One 10 cartridge type

TABLE 15. ELECTRODIALYSIS WITH REVERSAL (EDR):
INDEPENDENT AND DEPENDENT VARIABLES TO BE STUDIED
DURING FLUORIDE, NITRATE, ARSENIC, AND SELENIUM REMOVAL TESTS

Degree of pretreatment required: original design calls for only cartridge filtration (10 μ) and activated carbon for dechlorination. Minor equipment redesign will be required if pH adjustment, deep bed filtration or polyphosphates are found to be necessary to prevent membrane fouling

pH of product water: continous monitoring

% water recovery: (product flow/feed flow)100

% TDS removal: based on conductivity and gravimetric methods

Concentration histories of contaminants in product water: F^-, NO_3^-, As(III), As(V), Se(IV), Se(VI)

Concentration histories of common ions in product water: Ca^{++}, Mg^{++}, Na^+, Cl^-, HCO_3^-, $SO_4^=$

Degree of $CaSO_4$ supersaturation

Pressure drop across membrane stack: monitor only

Notes:

C_F = concentration of ion in feed
C_P = concentration of ion in product

additives, through manual valve V-1 (Figure 14) directly to the EDR unit. Because the unit was set up by the manufacturer with internal brine recycle to achieve 80% recovery, it is usually run in that mode rather than in the no recycle, 50% recovery mode. Product water flows through the overflow vessel and is collected in the treated water tank T-1 via pump P-1 directly from tank T-6 via pump P-6. Reject brine is wasted after flowing through wastewater tank T-5.

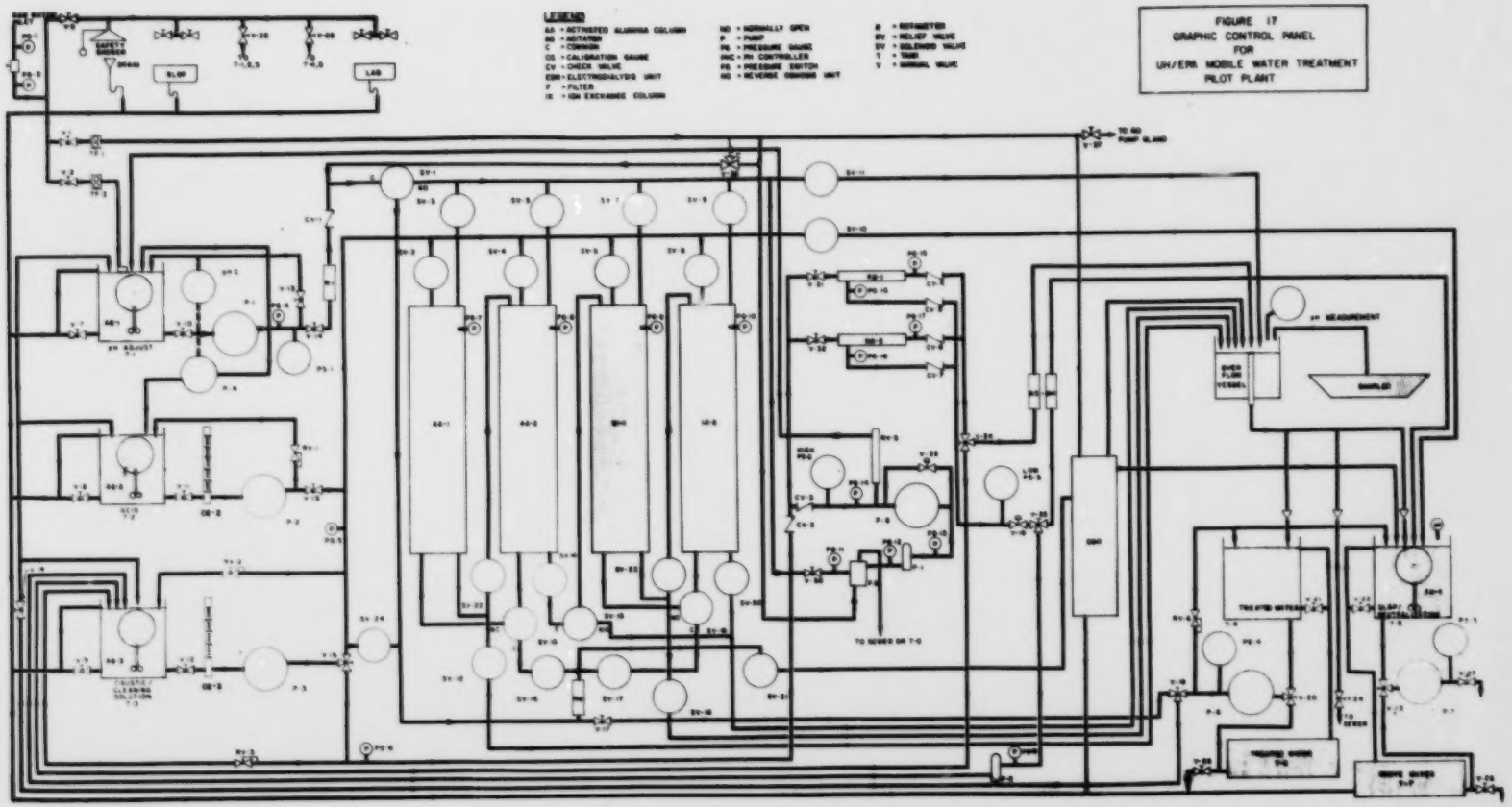
During operation of the EDR unit the current direction, brine and product flows are reversed each 15 minutes providing automatic membrane backwash at each reversal. According to the manufacturers and as verified by our experience to date (June, 1982), this allows for operation with minimum pretreatment, e.g., no pH adjustment, deep bed filtation, or anti-scaling additives are required in the usual case. Furthermore, Ionics claims that up to 400% supersaturation of $CaSO_4$ may occur on the brine side without serious fouling. However, we have not yet verified this latter claim in the field.

Before entering the EDR unit, raw water passes through a granular activated carbon filter F-1E (Figure 15) for dechlorination and then through a protective 10 cartridge filter F-2E mounted on the outside of the unit. Prior to entering the membrane stack, a portion of the raw water is metered through rotameter R-3E and blended with recycled brine in tank T-1E. The mixture is pumped (P-1E) through filters F-3E and F-4E into the membrane stack through either rotameter R-1E or R-2E. Flow into the stack is controlled by valves built into the rotameters and by the pump recirculating valve V-3E. Flow reversal is achieved by automatic, timed switching of the stack inlet solenoid valves SV-5E and SV-6E and the outlet solenoid valves SV-3E and SV-4E. The hydrogen, oxygen, and chlorine produced in the electrode compartments by the passage of current are vented from the brine recycle tank via a vent pipe to atmosphere above the trailer.

The operating variables to be studied during contaminant removal and desating with the EDR unit are listed in Table 15. An important variable which will be carefully studied is the degree of pretreatment required. Minimum pretreatment will always be attempted first but modifications may be necessary for successful operation. A typical set of effluent concentration histories of important species in product water from the EDR unit when it was treating Glendale, Arizona well water for nitrate removal is shown in Figure 16. Nitrate removal averaged 95%, sulfate 96%, bicarbonate 93%, and chloride 86%. As expected for non-ionic species, silica was not removed by the EDR unit. During this run, there was no pretreatent except the protective cartridge filter and the activated carbon filter. The carbon was actually unnecessary since the raw water contained no chlorine.

PROCESS INTERCONNECTIONS AND CONTROLS (Figures 17 and 23)

The four treatment processes just described are interconnected as shown in Figure 17, a photographic reduction of the actual color-coded graphic control panel in the pilot plant. There, the circles represent lighted, pushbutton switches which control the flow through the pilot plant. Not shown


LEGEND
FIGURE 17
GRAPHIC CONTROL PANEL
FOR
UH/ERA MOBILE WATER TREATMENT
PILOT PLANT

on the drawing are alarms which flash and sound when pumps go dry or when high or low pressure limits or pH limits are exceeded. In addition to the alarms, the affected pumps automatically shut off to protect the system.

Only one of the four systems is operated at a time. When a particular system is in operation, e.g., the ion exchange system, it is easy to follow the flow of water by following the sequence of lighted pushbuttons on the control panel (Figures 17 and 23). Although not shown in Figure 17, the graphic panel further simplifies tracing water flows as it is color-coded as follows:

black = pretreated water
blue = treated water
red = acid, base, or treatment chemical
brown = wastewater
green = raw water and service water
dashed lines = alternative flow paths for moveable hoses

Continuous pH monitoring and recording are provided for the pretreated process feedwater in tank T-1, and the process effluent water emanating from the overflow/sampling vessel. Both Uniloc pH monitors have high and low limit set points for on-off pH control and alarm triggering. The feedwater pH is controlled using the on-off pH meter output to operate the acid metering pump P-4. The effluent pH meter simply alarms when the pH is out of the preset range. The outputs from both pH meters are connected to a three-channel Rustrak recorder for continous pH recording if that is desired. The third recorder channel may be used to record the output from a conductivity meter or ion selective electrode.

COMMON HOLDING TANKS T-1 THROUGH T-7 (Figures 17, 19, and 26)

The basic flow for all processes is from left to right, i.e., from one of the feed tanks T-1, 2, or 3 to one of the effluent tanks T-4, 5, 6, or 7. Thus these tanks play a very important role in the operation of the pilot plant. Generally speaking, all process flow patterns during a treatment (exhaustion) step are initiated in tank T-1 where all pretreatment chemicals are added. Mixing is achieved in T-1 by agitator AG-1 and the recirculating water flow from pump P-1 through valve V-13. A special feature of the tank is that it may be used for the return of product and brine flows if recycling is desired.

The acid and caustic tanks T-2 and T-3 are used for chemicals addition, regeneraton, and cleaning. Each is fitted with a calibration gauge CG-2 or CG-3 of approximately 1.5L capacity. To calibrate one of the metering pumps, e.g., P-2, the outlet of the pump-feed tank T-2 is valved off by closing V-11 while the metering pump P-2 is running. The pump flow rate is calibrated without flow interruption by timing the rate of drop of the level in the calibrated plexiglas standpipe (calibraton gauge, CG-2). Return to service and gauge refilling are achieved by simply reopening valve V-11. Metering

pumps P-2 and P-3 are identical and any acid, base, or chemical may be fed through either of them from the appropriate tank. Tank T-3 is equipped not only for adding chemicals but also for cleaning the RO system. To achieve this, recycled cleaning solution is returned to the tank through cartridge filter F-2. During cleaning, excessive pressure is prevented in the cleaning system by relief valve RV-3 set at approximately 100 psig.

All process effluents from the system end up in one of three places: the treated water tank T-4, the slop/neutralization tank T-5, or the local sewer through valve V-24. The treated water storage system comprises two interconnected tanks: the 200-L polyethylene treated water tank T-4 in the pilot plant, and the 1100 L fiberglass storage tank T-6 mounted under the pilot plant. Overflow or underflow from the smaller tank (T-4) is either collected in the larger tank (T-6) or dumped to the sewer through V-25. Should the treated water be needed for backwashing, recycling, or solution preparation, it may be pumped to the appropriate destination from T-4 or T-6 via pump P-6 and valve V-19. To pump from the lower tank (T-6), the pump P-6 is primed by gravity flow from the higher tank (T-4). This same collection and pumping procedure may be used for the wastewater tanks (T-5 and T-7) except that wastewater from these tanks is not recycled to the process. Rather, it is drained to the sewer via V-26 or pumped to the wastewater tank in the pickup truck via pump P-7. Also, prior to disposal, acidic or basic wastewaters are neutralized by pumping the appropriate reagent directly into T-5 from either T-2 or T-3. Mixing during neutralization is achieved by agitator AG-4 and pH monitoring is done manually by portable pH meter.

To provide a better understanding of the total pilot plant and individual processes, detailed photographs of the process equipment (Figures 18 - 25) are given on the following pages.

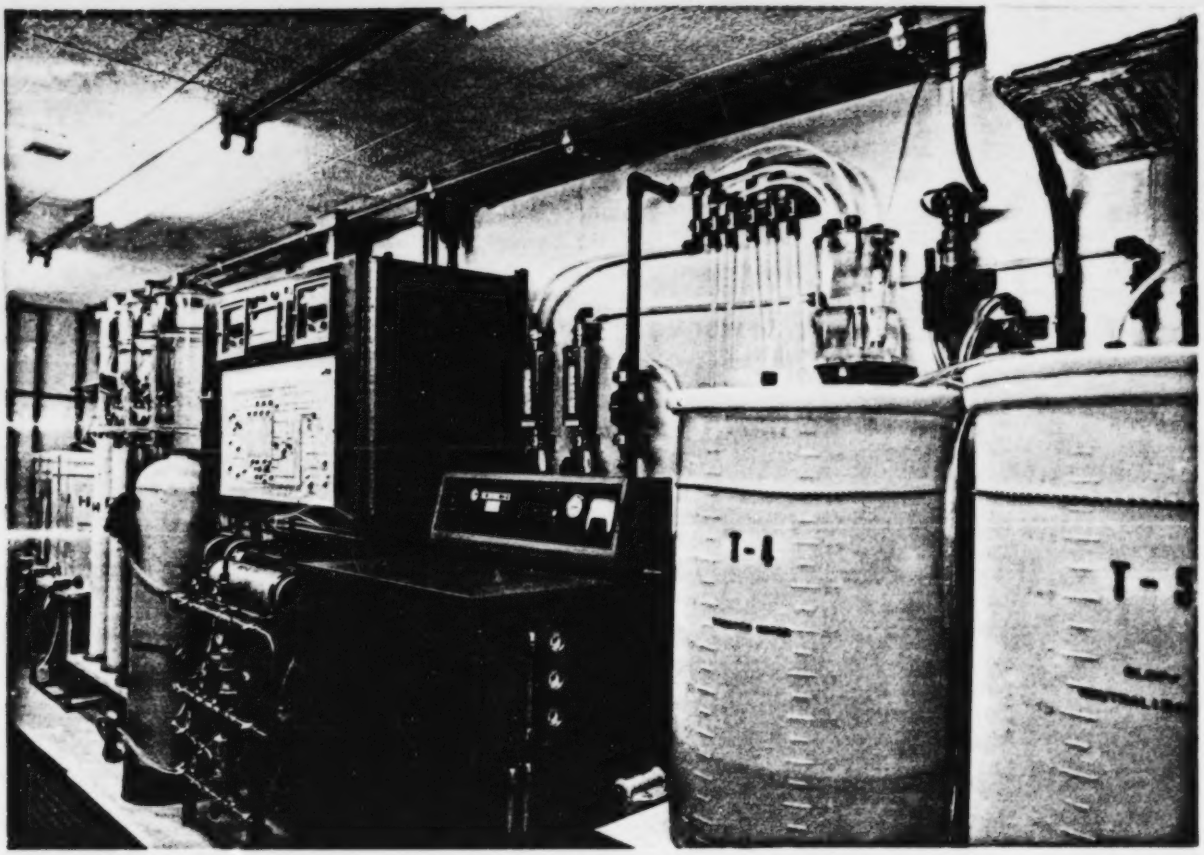


Figure 18. Treatment processes in pilot plant. From left to right: pH adjustment, acid and base tanks; alumina and ion-exchange columns; RO filter, control panel, RO system unit; overflow and sampling vessel, treated water tank and neutralization tank.

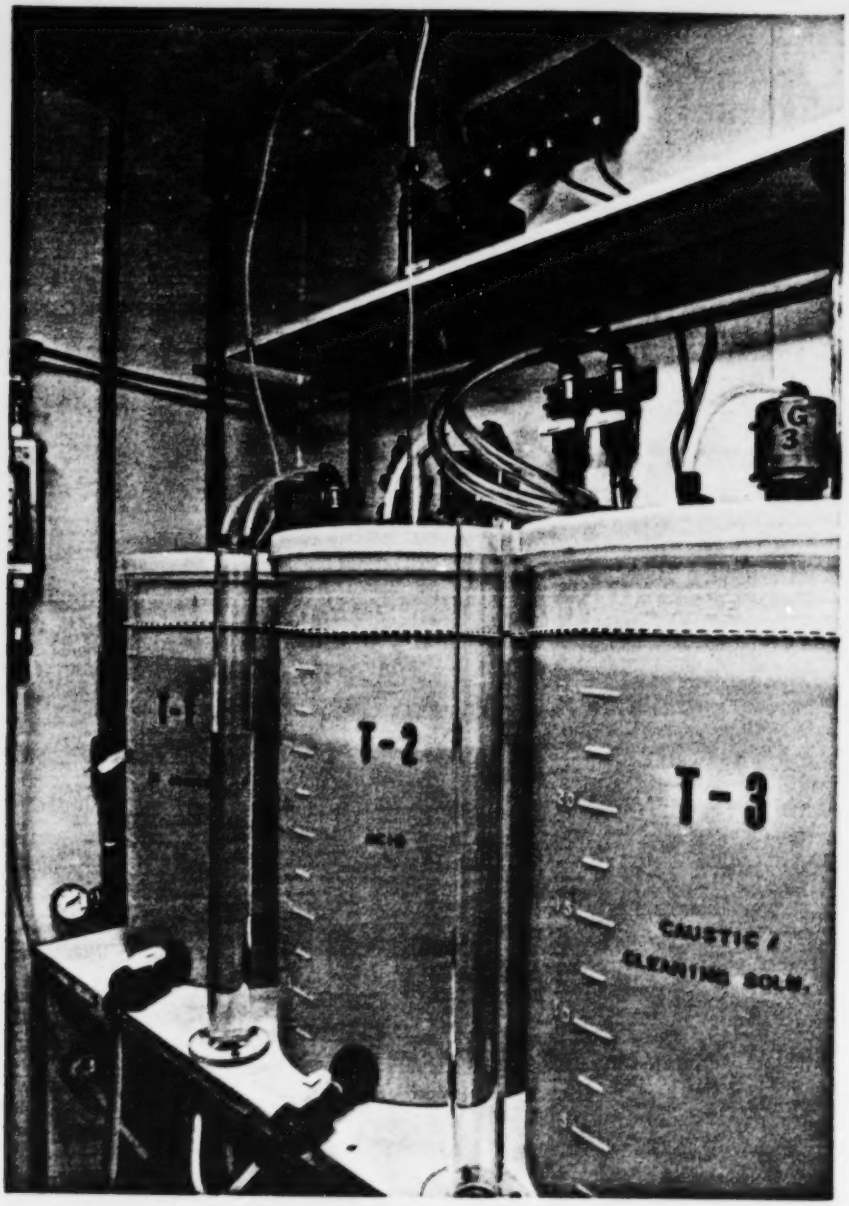


Figure 19. 100 ℓ (30 gal) pH adjustment, acid, and base tanks. From left to right: feedwater rotameter, tanks with agitators, acid metering pump on shelf above tanks, plexiglas flow calibration tubes in front of tanks, raw water and treated water supply valves on wall above tanks.

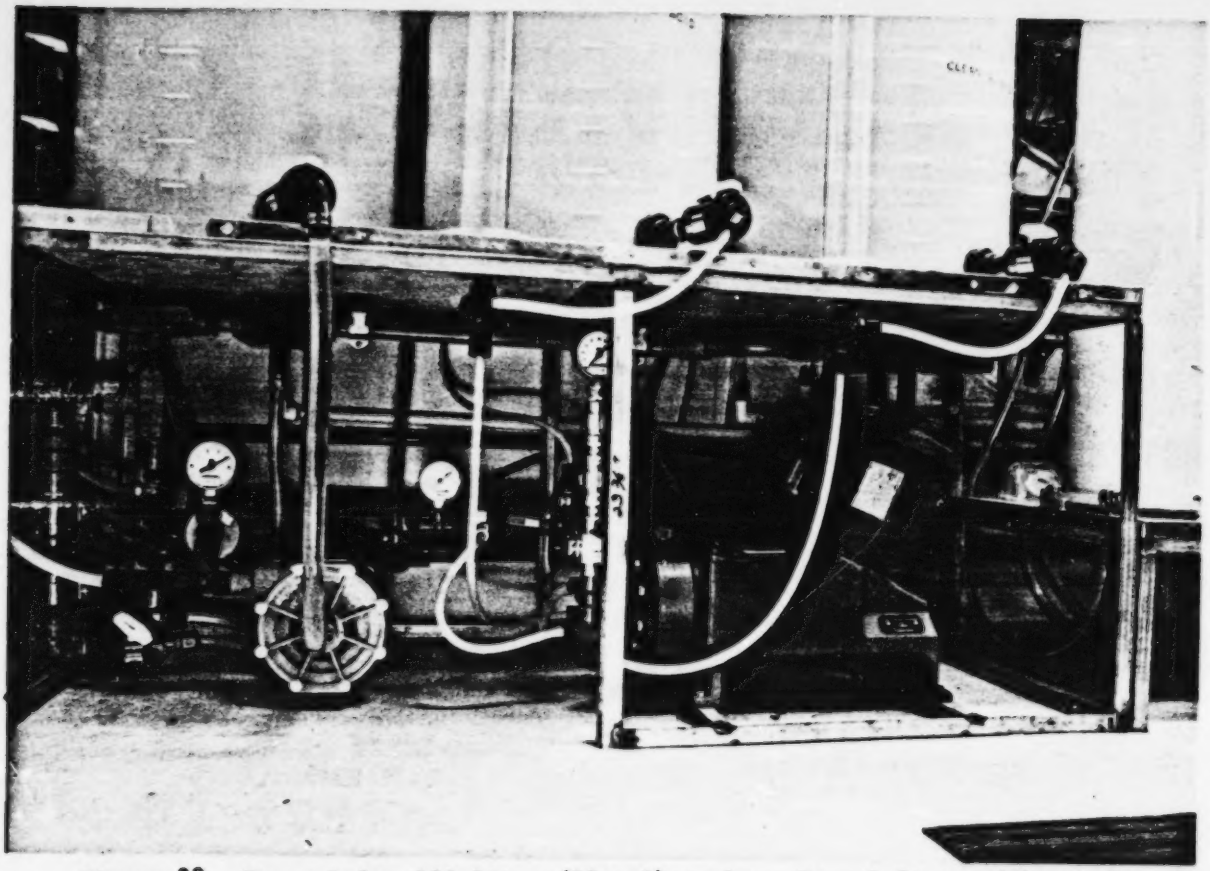


Figure 20. Pumps below 100 liter (30 gal) tanks. From left to right: pH probe assembly, 5 gpm CPVC centrifugal feed pump, acid and base metering pumps for regeneration and membrane cleaning.

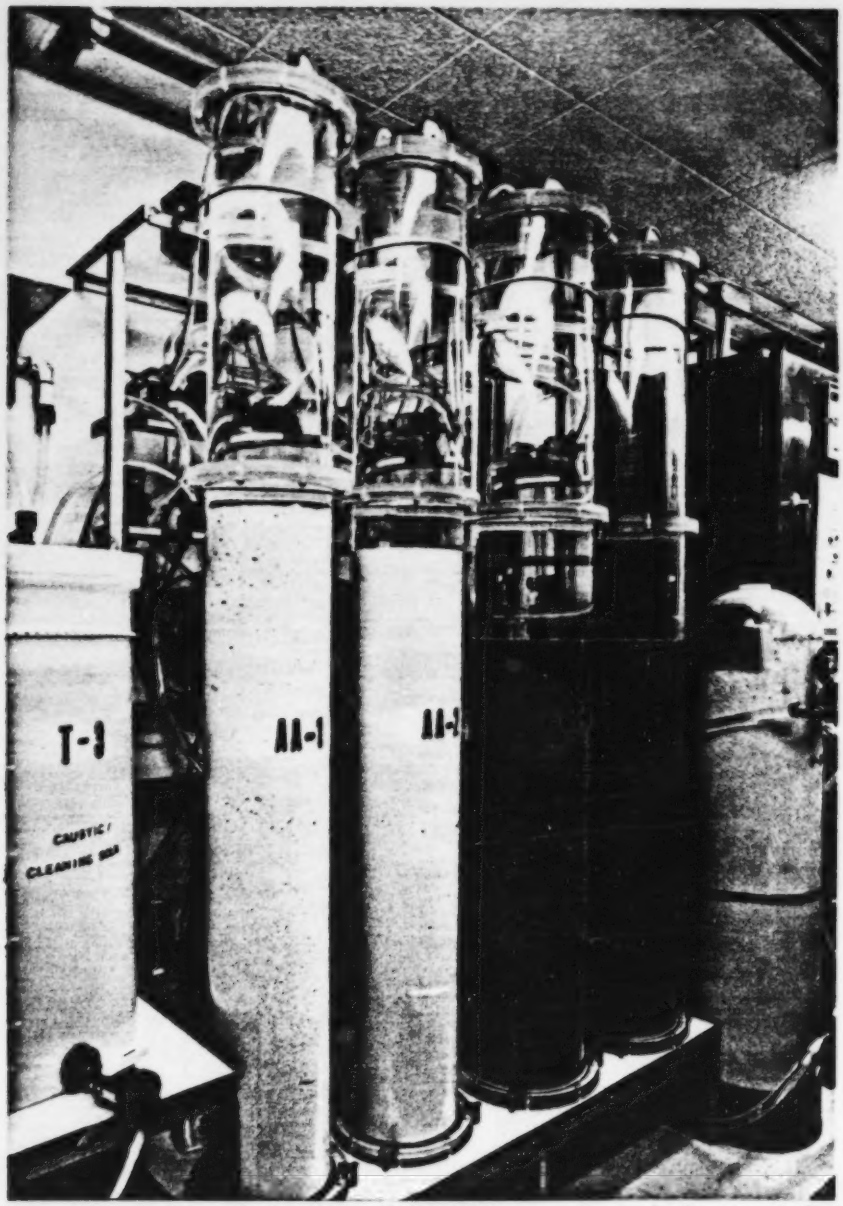


Figure 21. Columns and RO filter. From left to right: 8-inch diameter activated alumina columns, 10-inch diameter ion exchange columns, 13-inch diameter RO pretreatment filter. Valve shelves behind columns hold 24 electrical solenoid valves to control column operations.

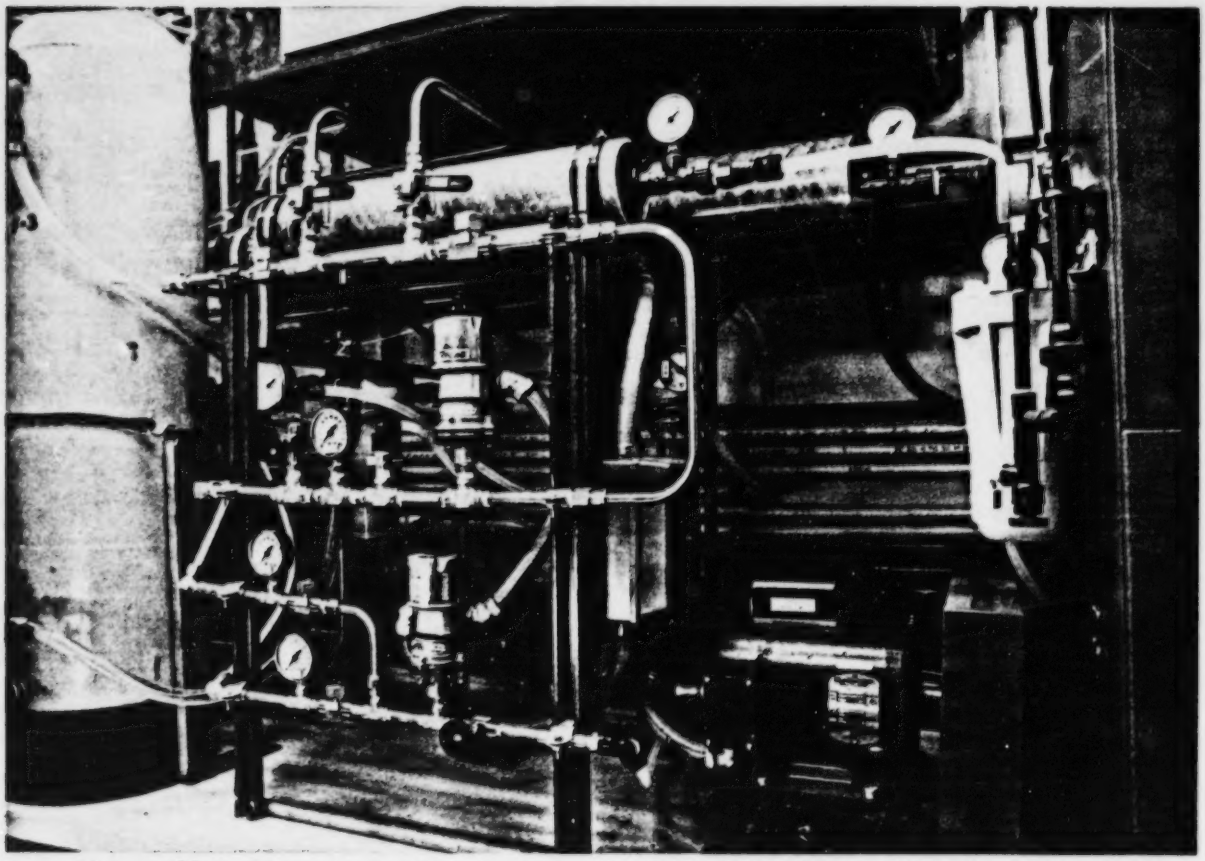


Figure 22. Reverse osmosis system. Pretreatment filter with AG media, duPont module (front), Dow module (rear); 3 hp belt-driven SS Moyno pump (bottom rear); flow control valves, relief valves, and pressure switches on front of frame.

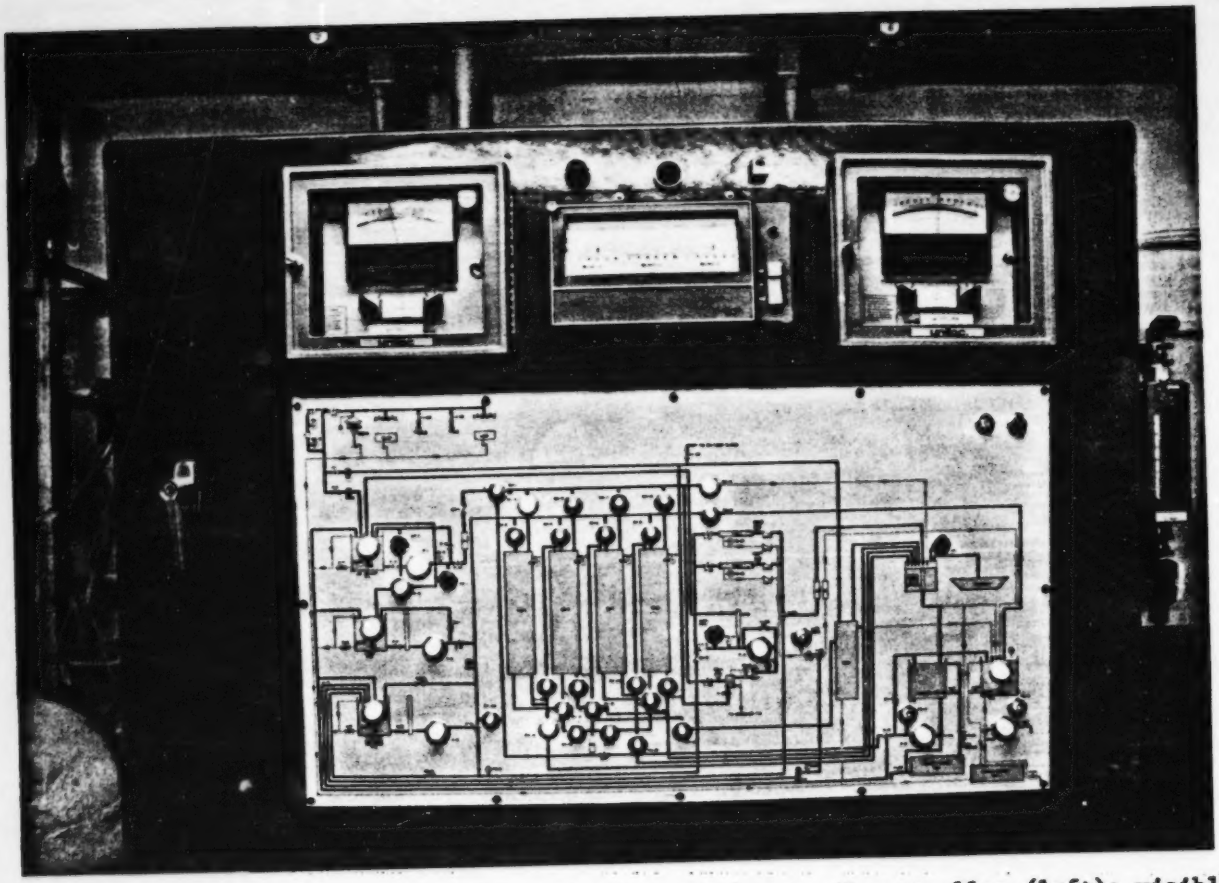


Figure 23. Fiberglas control panel box. Feedwater pH controller (left); visible and audible alarms, above 3-channel recorder, effluent pH monitor, color-coded graphic control panel: raw water (green), pH adjusted feed water (black), acid, base, and cleaning solution (red), treated water (blue), wastewater (yellow). Lighted pushbuttons indicate state of system.

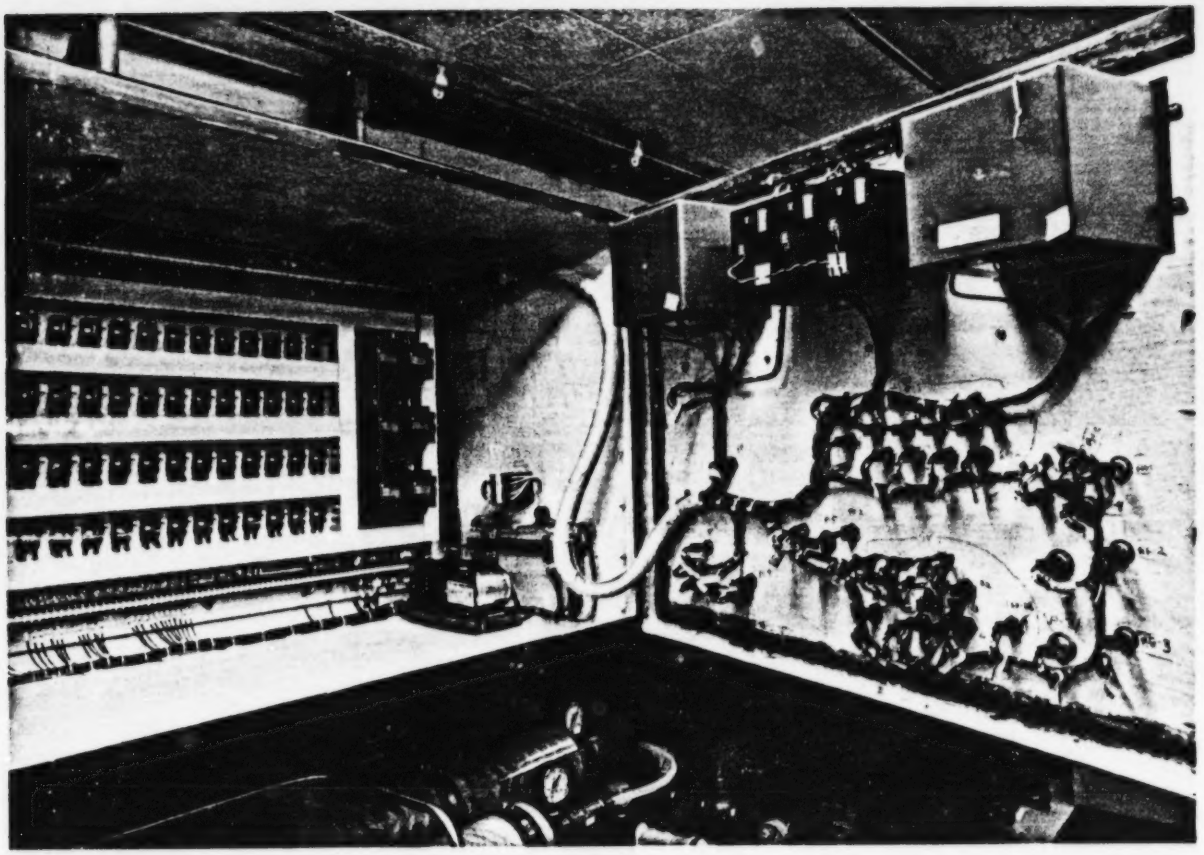


Figure 24. Interior of control panel box. From left to right: solenoid valve relays, motor starting controls, DC power supply, back of control panel door with pH meters and recorder above control switches.

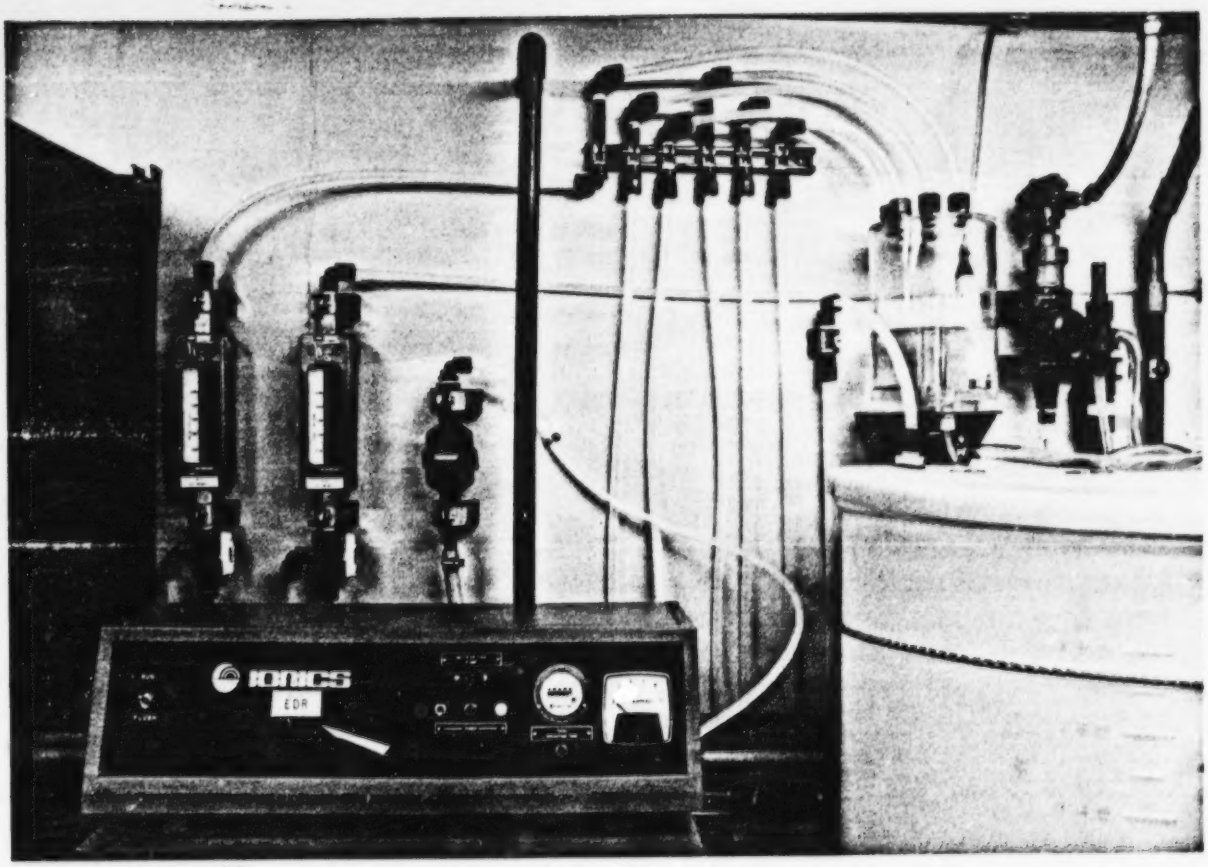


Figure 25. EDR unit and 200 liter (55 gal) tank. From left to right: EDR unit, RO product rotameter, RO reject flowmeter, EDR totalizing meter, plexiglas overflow and sampling vessel; PVC, effluent-pH probe assembly, and treated water tank.

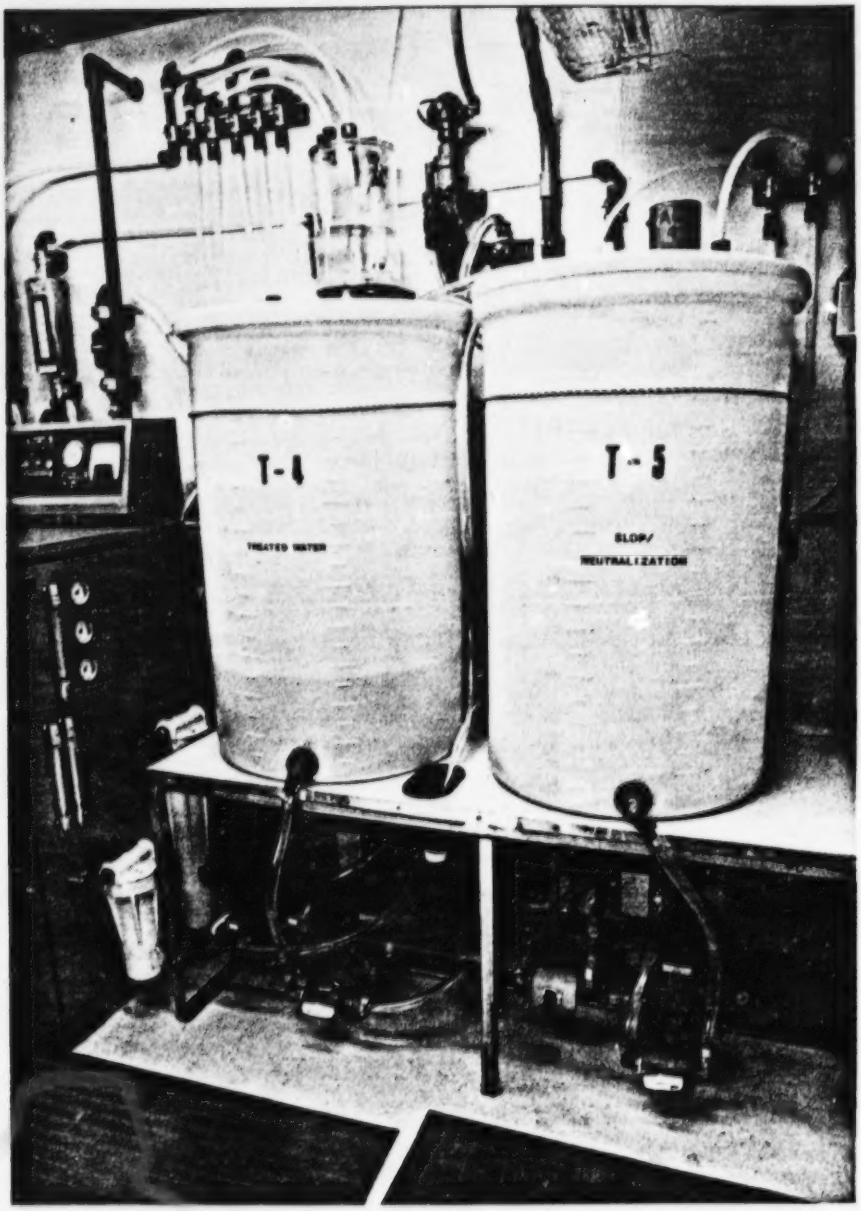


Figure 26. Final collection tanks and transfer pumps. From left to right: EDR unit, 200 ℓ (55 gal) treated water tank, neutralization tank with agitator, 5 gpm CPVC centrifugal pumps piped to tanks above and underbody tanks below (300 gal fiberglas underbody tanks not shown).

SECTION 4

PROJECT COSTS

The elapsed time to design and construct the trailer in a university setting was approximately 15 months from the date the work was begun in earnest (January, 1979). The total project costs to design, construct, debug and operate the trailer for seven months in its first field locaton were $262,000. This figure includes the cost of a one-year laboratory study on fluoride removal [4] at the University of Houston which was done in preparation or the field work on fluoride removal in Taylor, Texas. An estimate has been made of the cost to replace the mobile research facility as of October, 1981. The estimate assumes that the replacement would be essentially identical to the existing facility for which as-built drawings have been prepared. That estimate ($182,000) is detailed in Table 16 where it has been broken down into the approximate costs of the major components of the research facility. Note that the estimate does not contain major analytical laboratory equipment, viz., the ion chromatograph and the atomic absorpton spectrophotometer.

TABLE 16. OCTOBER 1981 REPLACEMENT COST ESTIMATE FOR UH/EPA RESEARCH TRAILER AND EQUIPMENT

Item	Installed Cost
10'x40' Trailer with air conditioning/heating, insulation, panelling, ceiling tile, moulding, painting and logos	$ 20,400.00
Activated Alumina Adsorption System 3000 gallons/day designed and built by UH	7,400.00
Two-Bed Ion-Exchange System 3000 gallons/day designed and built by UH	10,300.00
Reverse Osmosis System 3000 gallons/day designed and built by UH	20,000.00
Electrodialysis Reversal Unit Ionics, Inc. Model Aquamite I, 500 gallons/day	14,400.00
Electrical Control System for Pilot Plant Wiring and graphic panel designed and built by UH	12,000.00
Feedwater system with pH adjustment, UH designed and built	6,000.00
Acid feed system, UH designed and built	3,200.00
Caustic and cleaning solution system, UH designed and built	3,600.00
Service water plumbing system, UH designed and built	1,300.00
Effluent collection system, UH designed and built	11,300.00
Pilot plant furniture and miscellaneous equipment	8,200.00
General wiring and lighting, UH designed and built	4,000.00
Analytical laboratory equipment	23,500.00
TOTAL INSTALLED COST	$145,600.00
Administrative indirect cost (labor) to rebuild trailer @ 25 percent installed cost	36,400.00
Estimated Total EPA Trailer ReplacementValue(October 1, 1981)	$182,000.00

REFERENCES

1. U.S. Environmental Protection Agency Office of Water Supply, National Interim Primary Drinking Water Regulations, EPA-570/9-76-003, Sept., 1976; U.S. GPO, Washington, D.C.

2. APHA, AWWA, WPCF, "Standard Methods for the Examination of Water and Wastewater," 14th Edition, 1976, American Public Health Association, Washington, D.C.

3. U.S. Environmental Protection Agency Office of Technology Transfer, Methods for Chemical Analysis of Water and Wastes, EPA-625/6-74-003, June, 1974, U.S. EPA, Cincinnati, Ohio.

4. Singh, G. and Clifford, D., "The Equilibrium Fluoride Capacity of Activated Alumina." EPA-600/52-082, July 1981, U.S. EPA, Cincinnati, Ohio.

5. Clifford, D.A., "Processes for the Removal of Inorganic Contaminants from Water," Water Engineering and Management, Ref. Handbook, May 1982, pp. R31-R38..